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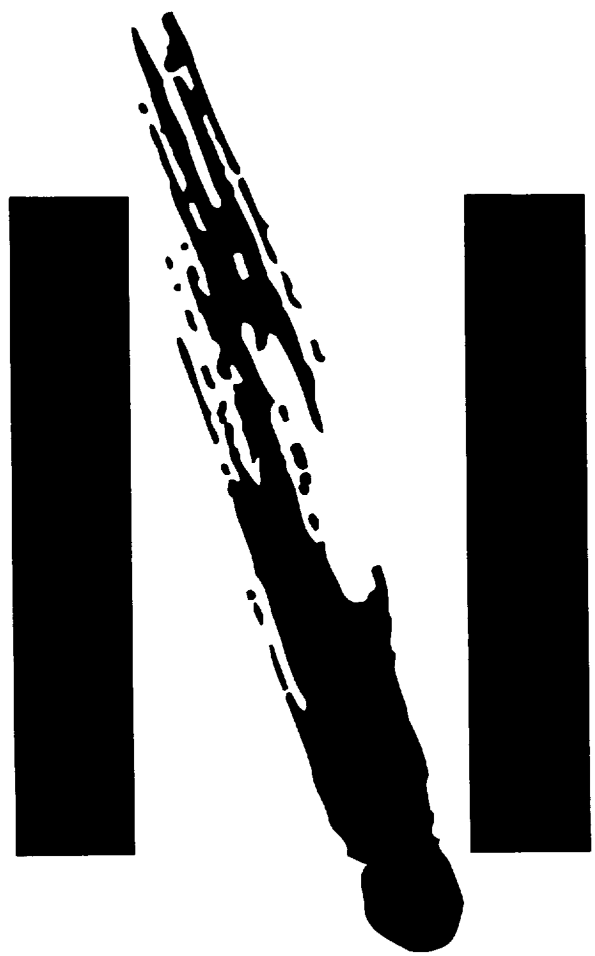
WORKSHOP ON METEORITES FROM COLD AND HOT DESERTS



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LPI/TR--95-02

WORKSHOP ON

METEORITES FROM COLD AND HOT DESERTS

Edited by

Ludolf Schultz, John O. Annexstad, and Michael E. Zolensky

Held at
Nördlingen, Germany

July 20–22, 1994

Sponsored by
Lunar and Planetary Institute
Max-Planck-Institut für Chemie
Rieskratermuseum Nördlingen

Lunar and Planetary Institute   3600 Bay Area Boulevard   Houston TX 77058-1113

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Introduction

Until 1969 only four meteorites had been found in the cold desert of Antarctica. Since that year, however, expeditions from Japan, the United States, and various European countries have recovered more than 16,000 meteorite specimens from remote ice fields. They represent approximately 3000–5000 distinct falls, more than all non-Antarctic meteorite falls and finds combined.

Four previous workshops have discussed the connection between Antarctic glaciology and Antarctic meteorites, their stranding surfaces, and differences between Antarctic and non-Antarctic meteorites. The cause of the differences among these groups is still under discussion. Two different lines have been explored: These differences have an extraterrestrial cause, or they are the result of secondary effects on Earth.

Recently many meteorite specimens of a new "population" have become available: meteorites from hot deserts. It turned out that suitable surfaces in hot deserts, like the Sahara in Africa, the Nullarbor Plain in Western Australia, or desert high plains of the U.S. (Roosevelt County), contain relatively high meteorite concentrations. For example, the 1985 Catalog of Meteorites of the British Museum lists 20 meteorites from Algeria and Libya. Ten years later, 543 meteorites finds from these two countries have been published in the Catalog and Meteoritical Bulletins.

Among Antarctic meteorites and those from hot deserts, several unusual and interesting specimens have been found. While the mean terrestrial age of Antarctic meteorites is of the order of 10^5 yr, that of meteorites from hot deserts is about 1 order of magnitude less. In spite of this age difference, weathering effects are more pronounced in the latter group. Thus, meteorites from hot deserts form another group that differs from Antarctic finds and modern falls with respect to terrestrial ages and the influence of the terrestrial environment on these rocks.

The idea to hold a workshop in which participants could discuss meteorite finds from cold and hot deserts was born in a EUROMET business meeting in 1992. EUROMET is a collaboration of over 50 European laboratories in 12 countries. Its purpose is to foster the collection, distribution, and interdisciplinary investigation of new meteorites and cosmic dust. EUROMET has accumulated over 1000 meteorite specimens in a series of expeditions to Antarctica and hot deserts.

The current workshop was organized to address the following points: (1) definition of differences between meteorites from Antarctica, hot deserts, and modern falls; (2) discussion of the causes of these differences; (3) implications of possible different parent populations, infall rates, weathering processes, etc.; (4) collection, curation, and distribution of meteorites; and (5) planning and coordination of future meteorite searches.

A first announcement of the planned workshop on "Meteorites from Cold and Hot Deserts" was mailed in fall 1993, and resulted in about 80 responses, which led to its definite planning. The workshop was held July 20–22, 1994, in Nördlingen, Germany, on the floor of the meteorite impact crater Nördlinger Ries, which was formed about 15 m.y. ago. The meeting was attended by 59 participants from 11 countries. In all, 32 papers were presented, and toward the end of the workshop several parties discussed their future plans to collect meteorites in hot deserts and in Antarctica. The last day of the workshop was devoted to a field trip to several outcrops of the Nördlinger Ries impact crater.

Following the workshop program, which appears in this volume, we provide summaries of the workshop presentations and discussions.

General Workshop Recommendations

As meteorite searches continue year after year, a mounting body of evidence about concentrations and physical parameters is gained. It seems, however, that a picture of what precisely is involved in each case or site is an elusive quantity. This workshop, above all, has pointed out the complexity of the situation and the need for more searches, more meteorites, and more investigations.

The conveners and most participants agreed that researchers and searchers should meet at least every three to four years to exchange ideas and to refine mechanisms. The workshop format prior to an annual Meteoritical Society meeting seems to be a workable vehicle.

Acknowledgments

We thank all participants of the workshop who contributed valuable research papers and participated in discussions. In the course of the preparation for the workshop, as well as during the meeting, able assistance was received from L. Franke (Mainz) and H. Stangel (Nördlingen).

We want to thank all sponsoring agencies, especially the Lunar and Planetary Institute, Houston, the Rieskratermuseum Nördlingen and its friends, the town of Nördlingen, the Verein Rieser Kulturtage, and the Max-Planck-Institut für Chemie, Mainz, for technical, logistical, and financial help.

Program

Wednesday, July 20, 1994

1200–1330 Registration
1330–1345 Welcome

1345–1545

METEORITE SEARCHES
Chair: M. M. Grady

R. P. Harvey
Current Research Activities of ANSMET: Recent Studies in the Walcott Névé Region

L. Folco, I. A. Franchi, M. Mellini, and C. T. Pillinger
1993/94 Antarctic Field Season: A Report on Activities Undertaken by the EUROMET/PNRA Meteorite Collection Expedition to Frontier Mountain, North Victoria Land

A. M. Reid, P. Jakeš, M. E. Zolensky, and R. McG. Miller
Recovery of Three Ordinary Chondrites from the Namib Desert, Western Namibia

I. A. Franchi, G. Delisle, and C. T. Pillinger
An Evaluation of the Meteorite Potential of the Jiddat Al Harasis and the Rub Al Khali Regions of Southern Arabia

M. E. Zolensky, J. W. Schutt, A. M. Reid, P. Jakeš, E. Martinez de los Rios, and R. M. Miller
Locating New Meteorite Recovery Areas

O. Gerel, A. Bischoff, L. Schultz, J. Schlüter, L. Baljinnyam, D. Borchuluun, C. Byambaa, and D. Garamjav
The 1993 EUROMET/Mongolian Expedition to the Gobi Desert: Search for Meteorites

1615–1715

MECHANISMS AND CHALLENGES
Chair: J. O. Annexstad

G. Delisle
Storage of Meteorites in Antarctic Ice During Glacial and Interglacial Stages

R. P. Harvey
Moving Targets: The Effect of Supply, Wind Movement, and Search Losses on Antarctic Meteorite Size Distributions

I. P. Wright, M. M. Grady, and C. T. Pillinger
The Acquisition of Martian Sedimentary Rocks: For the Time Being, Collection of Meteorites from Terrestrial Desert Areas Represents the Best Hope

1730–1830 Visit to the Rieskrater Museum

1900 Reception by the Mayor of Nördlingen at the Rathaus

Thursday, July 21, 1994

0830–0910

COLLECTIONS
Chair: R. S. Clarke

M. M. Lindstrom and R. Score
Populations, Pairing, and Rare Meteorites in the U.S. Antarctic Meteorite Collection

T. Geiger and A. Bischoff
Meteorite Find Locations, Shock Classification, and Pairing of 464 Meteorites from the Sahara, and the Mineralogical and Chemical Classification of Rare Types

0910–1120

WEATHERING EFFECTS
Chair: M. E. Zolensky

R. D. Ash and C. T. Pillinger
The Fate of Meteoritic Carbon in Hot and Cold Deserts

P. Bland, F. J. Berry, and C. T. Pillinger
Iron-57 Mössbauer Spectroscopy Studies of Weathering in Ordinary Chondrites from Roosevelt County, New Mexico

G. Crozaz
Pyroxene, the Indicator of Pervasive Trace-Element Mobilization in Antarctic Meteorites

U. Krähenbühl and M. Langenauer
Comparison of the Distribution of Halogens in Chondrites from Antarctica and from Western Australia

J. Newton, M. A. Sephton, and C. T. Pillinger
Contamination Differences Between CO3 Falls and Antarctic and Saharan Finds: A Carbon and Nitrogen Study

P. Scherer, L. Schultz, and Th. Loeken
Weathering and Atmospheric Noble Gases in Chondrites from Hot Deserts

1120–1230

COSMOGENIC NUCLIDES
Chair: D. W. G. Sears

M. Knauer, U. Neupert, R. Michel, G. Bonani, B. Dittrich-Hannen, I. Hajdas, S. Ivy, P. W. Kubik, and M. Suter
Measurement of the Long-Lived Radionuclides Beryllium-10, Carbon-14, Aluminum-26 in Meteorites from Hot and Cold Deserts by Accelerator Mass Spectrometry (AMS)

B. Meltzow, U. Herpers, W. Klas, B. Dittrich-Hannen, P. W. Kubik, and M. Suter
Beryllium-10 and Aluminum-26 Concentration in Carbonaceous Chondrites and Other Meteorite Types from the Sahara

K. C. Welten, L. Lindner, and K. van der Borg
Cosmogenic Beryllium-10 and Aluminum-26 in Lewis Cliff Meteorites

R. C. Reedy and J. Masarik
Production Profiles of Nuclides by Galactic Cosmic-Ray Particles in Small Meteorites

1330–1500

TERRESTRIAL AGES
Chair: M. E. Lipschutz

A. J. T. Jull, A. W. R. Bevan, E. Cielaszyk, and D. J. Donahue
Carbon-14 Terrestrial Ages and Weathering of Meteorites from the Nullarbor Region, Western Australia

K. Nishiizumi
Terrestrial Ages of Meteorites from Cold and Cold Regions

R. Wieler, M. W. Caffee, and K. Nishiizumi
Exposure and Terrestrial Ages of H Chondrites from Frontier Mountain

F. Wlotzka, A. J. T. Jull, and D. J. Donahue
Carbon-14 Terrestrial Ages of Meteorites from Acfer, Algeria

P. H. Benoit and D. W. G. Sears
Terrestrial Age Clustering of Meteorite Finds from Sites in Antarctica and Hot Deserts

1530–1700 **DIFFERENT POPULATIONS?**
Chair: G. Crozaz

S. F. Wolf and M. E. Lipschutz
Yes, Meteorite Populations Reaching the Earth Change with Time!

S. F. Wolf and M. E. Lipschutz
Applying the Bootstrap to Antarctic and Non-Antarctic H-Chondrite Volatile Trace Element Data

Th. Loeken and L. Schultz
The Noble Gas Record of H Chondrites and Terrestrial Age: No Correlation

P. H. Benoit and D. W. G. Sears
The Antarctic Collection and Changes in the Meteorite Flux Over Time: The Lingering Death of a Subgroup of H Chondrites

Y. Miura
Difference of Three Meteorite Groups in Orbits and Fall Time

1700–1800 **FUTURE PLANS**
Chair: M. M. Lindstrom

Contributions by
G. Delisle, R. P. Harvey, H. Kojima, C. T. Pillinger, and A. M. Reid

1930 **PUBLIC LECTURE**

G. Delisle and L. Schultz
Meteoriten aus Heissen und Kalten Wüsten: Suche und Wissenschaftliche Bedeutung

Friday, July 22, 1994

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THROUGH THE RIES CRATER
Led by M. Schieber and G. Pösges

Contents

Summary of Previous Workshops

Prior to the present workshop there have been four workshops specifically dealing with Antarctic meteorites, but none on specimens from hot desert areas. The significance of the finds from dry areas (polar and desert) has been such that it was time to combine the regions into one meeting. It is also appropriate to briefly describe the previous meetings as background for this presentation.

The first workshop was held at the Lunar and Planetary Institute in Houston, April 19–21, 1982. The conveners were C. Bull and M. E. Lipschutz from Ohio State University and Purdue University respectively. The general theme of the meeting was the interface between Antarctic glaciology and meteorites found principally in blue ice areas.

The two-day session was characterized by papers on meteorites, collecting programs, and the glaciology of specific and general sites. The subjects ranged from the Japanese and American collection programs to the glaciological history of the Allan Hills and Yamato blue ice fields. Papers on meteorite curation, characterization, mineralogy-petrology, and terrestrial ages helped complete the understanding of the processes involved for the workshop participants.

This first meeting was principally a learning effort for most attendees, and the report [1] reflected that fact. It is a compendium of information known at that time and also contains specific recommendations for future studies. The report stressed the need for studying blue ice areas as meteorite concentration regions and utilizing the specimens as tracers of ice sheet movement. The importance of viewing these phenomena (meteorites and glaciology) as a broad-based science of interest to meteoriticists, glaciologists, climatologists, geologists, and geophysicists was also emphasized.

The second workshop, sponsored by the Lunar and Planetary Institute, Houston, the Max Planck Society, and the International Association of Geochemistry and Cosmochemistry, was held at the Max-Planck-Institut für Chemie in Mainz, Germany, July 10–12, 1985. The conveners were L. Schultz and H. Wänke from the Max-Planck-Institute für Chemie in Mainz and J. Annexstad, then at NASA Johnson Space Center. This workshop was decidedly international in flavor, with 23 speakers and a total of 78 participants from 12 different countries. The purpose of this meeting was twofold: (1) to explore the possibility of general procedures for collection, curation, handling, and distribution of specimens worldwide; and (2) to discuss further the relationship between Antarctic meteorites and Antarctic glaciological processes. The workshop was held in Mainz just prior to the Meteoritical Society Meeting in Bordeaux.

Workshop participants summarized in a series of papers subtopics such as field work, general Antarctic glaciology, concentration mechanisms, weathering processes, terrestrial ages of specimens, rare types found, and compositional differences between Antarctic and non-Antarctic specimens.

It should be noted that this workshop brought to the attention of many the importance of Antarctic specimens and their relationship to ice dynamics. The workshop report [2] emphasized the need for more cooperation among nations and called for increased participation of glaciologists in understanding meteorite concentration processes. It also called for early dissemination of specimens for scientific investigation soon after collection from those countries finding meteorites.

The third workshop was entitled "Antarctic Meteorite Stranding Surfaces" and was held July 13–15, 1988, at the University of Pittsburgh. Sponsors were the National Science Foundation (Division of Polar Programs) and the LPI. The conveners were W. Cassidy and I. Whillans from the University of Pittsburgh and Ohio State University respectively. Twenty-four participants attended and 29 presentations were given with a primary focus on glaciological processes.

The reference to meteorite collection sites in Antarctica as stranding surfaces was first proposed by Cassidy in the second workshop. This idea, coupled with the discovery of thousands of new specimens, prompted renewed interest in the glaciology of blue ice areas as regions of climatic and ice sheet information over long time periods. The three most important aspects of stranding surfaces are their relationship to climate change, their relationship to ice volume change, and as a source of cosmogenic materials. As noted in the report [3], the focus of the workshop was on the first two topics because it seemed that the importance of these meteorite finds to glaciology was being underemphasized.

New material presented at the workshop showed the complexity of the glaciological problem and how important future studies would be on ice sheet dynamics. These subjects included (1) verification of subglacial obstructions to ice movement, (2) measurements of temperature variations within meteorites exposed on the surface, (3) measurements of the uncovered ages of terrestrial rocks near the stranding surfaces, (4) tephra deposits in the ice as possible time horizons, (5) the complicated stratigraphy of ice at stranding surfaces, (6) sampling of ice horizontally at collection sites, (7) O isotope measurements of stranding surface ice, and (8) the microclimate of the surfaces.

In general, the workshop participants urged the continued collection of meteorites from Antarctica and the glaciological investigation of stranding surfaces. The entire problem of meteorite transport and concentration is imperfectly understood and appears to be a subject complicated by a number of interrelated factors. As noted by the editors, "The situation [meteorite recovery in Antarctica] appears to present a classic opportunity, in which one unexpected discovery, Antarctic meteorites, leads not only to fundamental insights in its own field but also opens exciting directions in another" [3].

The next workshop was held in Vienna, Austria, on July 27–28, 1989, and was sponsored by the LPI and the University of Vienna. Conveners were C. Koeberl, University of Vienna, and W. Cassidy, University of Pittsburgh. It was entitled "Differences Between Antarctic and Non-Antarctic Meteorites" in response to the large numbers of recovered specimens from Antarctica that appear to differ from or are underrepresented in non-Antarctic collections.

The meeting was composed of 5 sessions attended by 45 participants from 10 different countries. Twenty-five papers were presented, with ample time for discussions. The sessions ended with a summary, recommendations, and some closing remarks.

Among the participants there seemed to be general agreement that there were measurable differences between Antarctic and non-Antarctic meteorite specimens. However, as pointed out by one summarizer, it was unclear whether the differences are due to weathering or are of preterrestrial origin. The question of weathering was considered important, but the classification scheme used did not reflect a useful parameter for significant studies. Another problem noted was that of pairing of the Antarctic finds among the rare and unusual types recovered.

As pointed out by some researchers, the cause of the observed apparent differences could be principally due to weathering effects. This was especially true for the O isotopic data and spallogenic noble gases, where contamination is not a problem, and no detectable differences of significance are observed. Such is not the case for C, where differences are found between Antarctic and non-Antarctic carbonaceous chondrites, and weathering/contamination parameters do influence the data.

Another factor noted as a possible alternative explanation was that of population differences based upon mass, number, and type. Comparisons between Antarctic finds and non-Antarctic falls clearly show mass differences, with Antarctic meteorites being on the whole smaller, but workshop participants did not agree on the reasons. There seems to be some disagreement among researchers on the meaning of statistical analysis employed to demonstrate a change of flux over time or the processes of impact and recovery. The timescales associated with meteorite impact and their association with posited meteoroid stream life times implies a dramatic change in meteorite sources in a very short and possibly unreasonable time period. Therefore, the participants were again perched on the horns of the dilemma—are the noted differences real or an artifact?

In the general workshop summary [4] it was noted that although differences had been recognized, the causes were not accepted unanimously among the workshop participants. The obvious differences are shown to be type frequencies among rare or unique specimens, textures, terrestrial ages, and mass abundances. The real question was whether or not either population (Antarctic or non-Antarctic) is representative of a parent body population. Even with the present data in hand, it seems that more specimens are needed to help complete an incomplete dataset. Although the Antarctic specimens do represent the best sample set presently available, the advent of new specimens from the dry desert areas of the world will add important new information.

References: [1] Bull C. and Lipschutz M., eds. (1982) *Workshop on Antarctic Glaciology and Meteorites*, LPI Tech. Rpt. 82-03, LPI, Houston. 57 pp. [2] Annexstad J. O., Schultz L., and Wänke H., eds. (1986) *Workshop on Antarctic Meteorites*, LPI Tech. Rpt. 86-01, LPI, Houston. 119 pp. [3] Cassidy W. A. and Whillans I. M., eds. (1990) *Workshop on Antarctic Meteorite Stranding Surfaces*, LPI Tech. Rpt. 90-03, LPI, Houston. 103 pp. [4] Koeberl C. and Cassidy W. A., eds. (1990) *Workshop on Differences Between Antarctic and Non-Antarctic Meteorites*, LPI Tech. Rpt. 90-01, LPI, Houston. 102 pp.

Summary of Technical Sessions

METEORITE SEARCHES

This session was basically a report of field searches in Antarctica and hot desert areas. Each speaker gave an account of the expedition's successes, failures, ancillary work and/or results, and a personal view of the trip. The information given was helpful for anyone evaluating a particular area for future meteorite searches.

A key paper given at the session was by Zolensky et al. on the criteria necessary for locating new meteorite search areas. As an example, to date, the areas searched in Antarctica have been defined primarily by the existence of blue ice, which emerges or is seen in the vicinity of mountains, nunataks, and subglacial rises. The majority of specimens found in these areas appear to accumulate in upstream valleys where the ablative effects are strongest. Wind also plays an important role by fostering ablation and concentrating the smaller specimens along firn-ice boundaries. Therefore, it is of utmost importance to note and study the effects of ablation, wind, and ice flow in an attempt to understand the concentration process. This is especially true in Antarctica where the general criteria are applied, but each ice field seems to exhibit special characteristics not readily explainable in a general sense.

In applying a set of criteria, Zolensky noted that both cold and hot deserts share similar physical characteristics. The Antarctic experience was a key factor because the region has been searched with great success for the last two and a half decades.

The criteria applied were low humidity, low fluvial activity, low terrestrial rock accumulations, rapid burial of specimens, recent deflation, a rigid support surface, a thin cover of sand or snow, and sufficient accumulation time (100 k.y. or so). In an application of these parameters the authors chose Lea County, New Mexico, the Atacama in Northern Chile, and the Namib in Namibia as possible hot desert search areas. All selection parameters were not present in any one site, but a few specimens were found in each, which indicates the value of applying constraints to areas that seem promising. Where the most criteria were satisfied the success rate of meteorite recovery was higher. Zolensky noted that luck and a searcher's ability to differentiate meteorites from local rocks played a large part in find success.

A very successful Antarctic field season was reported by Harvey, who recounted the visit in 1993–1994 to the Walcott Névé. The search team found 857 specimens in a region labeled Foggy Bottom. Most were ordinary chondrites representing several showers, although one specimen may be of lunar origin. The region has been so productive that Harvey noted it will become a major test site for ice movement and ablation studies. Ice flow there is complex, with a two-directional flow around a moraine and over a subglacial escarpment. The majority of specimens were found along the western edge of the ice tongue.

Harvey also reported some total statistics that characterize the U.S. search program ANSMET (Antarctic Search for Meteorites) since its inception in 1976. At the time of the workshop, 7078 specimens had been recovered, 8813 subsamples had been supplied to 260 researchers in 20 countries, and 55 people from 45 institutions in 16 countries had participated in searches. These statistics show elegantly how diverse and successful the U.S.-supported program has become.

EUROMET has modeled its Antarctic search program after the U.S. system and continues to reap success in the Frontier Mountains region. Folco et al. reported that in the 1993–1994 season to the Frontier Mountains the team recovered 59 specimens, 29 of which were found in Meteorite Valley, the site of finds during earlier expeditions. EUROMET has installed a strain net at an eolian trap located upwind of a depression and has established a "rock race" (rate of rock movement by wind action) system. Results to date indicate that wind speeds in the area tend to exceed those in the Allan Hills and easily move specimens up to 170 g. An interesting feature of this region is that the depression is believed to be the result of the collision of two ice streams, one flowing north, the other flowing south around the Frontier Mountains. Meteorite specimens appear to come only from the southern stream, which points out again the need to study each collection site for its unique concentration and identifying characteristics. The authors also noted the need for more work in the area to define more clearly the age of the collecting region and its meteorite recharge rate.

The remaining three speakers in this session discussed meteorite searches in hot desert areas, which, in each case, satisfied some but not all of the Zolensky criteria. The first was A. Reid who, along with three others, searched a portion of the Namib Desert in Western Namibia. The expeditioners searched five areas, of which four yielded no specimens, but in the fifth, three new chondrites were found. The four unsuccessful areas were characterized by high sand movement and a high incidence of coastal fog and a significant sand/pebble cover. The team searched interdune corridors, old fan delta terraces, and near the Roter Kamm impact crater without success. The three specimens found (one had 27 fragments) were located in a deflation area near Walvis Bay (no longer part of South Africa) away from the coastal areas and fog. All the meteorites found were L chondrites (two 5s and one 6) and two showed extreme weathering.

Gerel et al. reported on the 1993 EUROMET Mongolia Expedition to the Gobi Desert, which is a 2000–1000-km region in southern Mongolia. The search team was hampered by the lack of sufficient map control, very high rainfall for the region (the wettest year in a generation), and the large influx of animals to the region. Although satellite pictures showed that this region has good prospect criteria, the combination of moisture, animals, volcanic rocks, and insufficient detailed maps contributed to their lack of success. The prediction is that under better conditions this may be a productive region.

Franchi et al. reported on searches in southern Arabia, specifically in the Jidad al Harasis and the Rub al Khali regions. These two areas have produced 24 specimens in the past, with all being found by personnel engaged in oil exploration in the 1950s. The reconnaissance search in 1993 by the authors added two more specimens to the total. The Jidad al Harasis is a 60,000-km^2 region of playa deposits, with extensive track remnants of oil exploration activity. The Rub al Khali, on the other hand, is a 550,000-km^2 sand sea composed of extensive longitudinal dunes. The interdune areas are judged to be Pleistocene lake beds that would be productive regions to search. The terrestrial ages of the meteorites found are between 15,000 and 31,000 yr at the Jidad al Harasis and 6400–27,500 yr at the Rub al Khali. Although these deserts are highly arid, the severe weathering of the finds and the low terrestrial ages suggest that preservation conditions may be rather poor.

The recovery rate of specimens from the hot desert areas comes nowhere near that in Antarctica. It appears that the ice burial alone creates a preservation system that far exceeds that of hot deserts. On the other hand, sand movement and periods of non-aridity may be more pernicious to meteorites than previously expected. In any case, it seems to be the opinion of the speakers of this session that searchers should continue in both hot and cold deserts, but with a closer look at the criteria that define a good meteorite search area.

METEORITE COLLECTIONS

Well-maintained meteorite collections are the bedrock upon which the science of meteoritics has been constructed. In the past two decades the number of available meteorites has been more than doubled by the recovery of specimens from cold and hot deserts, a testament to the continuing value of meteorite recovery expeditions. Unfortunately, only two formal presentations were given at the workshop concerning meteorite collections. Therefore, we have appended a brief section on all major repositories of desert meteorites at the end of this workshop summary.

M. Lindstrom described the population statistics for the Antarctic meteorites recovered by the ANSMET expeditions. A perennial problem with this description is how to account for specimen pairing, since most of the ordinary chondrites (the bulk of the collection) have received insufficient characterization to permit pairing to be directly determined. Lindstrom's analysis indicates that, for example, 70% of the Antarctic pairing groups have 3 members, and 30% have 10 members. She suggests that a good average value for chondrite pairing groups is five. By applying this simple pairing correction value to the full population of Antarctic chondrites, she finds that the relative numbers of H, L, and LL Antarctic finds match modern fall statistics, so that there is no difference in these populations when they are viewed in this manner. Application of this simple pairing statistic suggests that there are approximately 1300 separate known Antarctic falls represented in the ANSMET collection. Lindstrom further finds that most rare types of meteorites (except lunar and SNC meteorites) are small in mass, and that the ease with which small masses are recognized on the ice provides a bias in their collection frequency in the Antarctic, something that has been previously noted. An interesting remaining question is what the maximum distance is between paired Antarctic meteorites, and the way in which this value could be modified by ice movement.

T. Geiger and A. Bischoff then described the current state of the meteorite collections from the northern Sahara Desert. Future expeditions to the Sahara will have to have the full cooperation of the host countries, which has not always been achieved in the past. It is notable that so many carbonaceous chondrites have been found in the Sahara, more than from other hot deserts. Two paired CR chondrites, El Djouf 1 and Acfer 059 (together with other paired samples), were found 600 km apart, which appears to be an extraordinarily large length for a strewn-field.

WEATHERING EFFECTS

A critical factor in any investigation of meteorite finds is recognition of the extent and type of terrestrial alteration. Even the Antarctic environment, where chemical weathering is minimized by low temperatures, is capable of producing significant changes in meteorites. A recent goal of some meteoriticists has been to contrast the weathering produced in cold vs. hot deserts, so that the meteorites found there (often with considerably different terrestrial ages) can be properly compared.

R. Ash discussed the character and fate of C in meteorite finds in deserts. He indicated that chondrites generally have extraterrestrial C in the following relative amounts: macromolecular <90%, carbonate <10%, organic <10%, and presolar <1%. In general, macromolecular C is broken down by pyrolysis in hot deserts, so most extraterrestrial C is lost here. Among ordinary chondrite finds, Roosevelt County 075 has the highest C, but the bulk of this is terrestrial organic C, rather than terrestrial carbonate or extraterrestrial material. Contamination by terrestrial carbonates appears to not be a problem with the Roosevelt County meteorites. Workshop participants pointed out that carbonate leaching is an important process during "wet" interglacial periods in the southwestern U.S. Finally, Ash found that in the case of the

Saharan chondrites, which were found on a limestone plateau, carbonate is the most important terrestrial C contaminant. An important conclusion is that the type and degree of C contamination is to some degree specific to the find site, a factor that must be accounted for in any comparison of meteorites found in different locations.

P. Bland et al. described the results of their efforts to formulate an improved meteorite weathering scale, superior to those based upon general rustiness and alteration of mafic silicates. Their new scale is based upon the assumption that all ferric iron in meteorites is due to terrestrial oxidation of originally ferrous iron, and employs ^{57}Fe Mössbauer spectroscopy. They conclude that their scale may be useful for meteorites with high terrestrial ages, but that for short ages the spectra are difficult to interpret. R. Walker suggested that the application of low-temperature Mössbauer spectroscopy would be profitable here. There were also suggestions in their results that H chondrites weather faster than L chondrites (as might be expected from the former's greater metal content). It is interesting that all the new Atacama meteorites are L chondrites (see the abstract by Zolensky et al.). They also extrapolated the curve on a plot of ferrous/ferric iron vs. terrestrial age for Roosevelt County meteorites, to find that at a terrestrial age of approximately 60 k.y. all olivine should have weathered away in hot deserts. They suggested that 60 k.y. might be considered a maximum terrestrial age for hot deserts. However, Roosevelt County meteorites have already been shown to have terrestrial ages ranging up to approximately 100 k.y. (see the abstract by Zolensky et al.). Bland et al. point out that carbonates and hydrous silicates could, in some situations, armor mafic silicates and thereby provide a certain degree of protection against further alteration. Also, the changing temperature and aridity conditions attending regional climatic change would have further complicated this situation. Thus, the disagreement here may be due to the complex history of Roosevelt County meteorites, which first experienced at least one cycle of oxidation, burial, and carbonate contamination, followed by deflation (excavation), dissolution of carbonates, and then further oxidation.

G. Crozaz suggested that meteoritic pyroxene contains a record of trace-element (REE) mobilization during alteration in Antarctica, which can be read with the ion probe. Although eucrites appear to have been affected the most by this particular alteration, she cautioned that all Antarctic meteorites have probably been chemically compromised to some extent. The major implication is that petrogenetic modelers should beware because even major elements could have been affected by chemical weathering in Antarctica.

U. Krähenbühl et al. compared the distribution of halogens in chondrites from Antarctica and the Nullarbor Plain. For Antarctica they reported an anticorrelation between F/I and distance from the ocean, due probably to the fact that F is in sea spray while the source of I is less mobile, biogenically produced methyliodide. They also found that halogen contamination of Antarctic meteorites increases linearly with terrestrial age, but that there was a poor correlation of these with visible degree of weathering, which is a known problem. The major Cl contamination in the Antarctic is from subaerial exposure, which means that the predominant orientation of these meteorites on the ice can be determined (most of the Cl should be on the top). The situation for Nullarbor meteorites is not simple. There is heavy Cl and Br contamination for these samples, and there is no apparent correlation of this with terrestrial age. This may be due to the accelerated rate of halogen mobility at higher temperatures. They find evidence that some process removed early surface contamination from the Nullarbor meteorites (water?), and that it is therefore likely that other species have been similarly mobile at this time.

J. Newton et al. reported on a comparison of C and N contamination for CO3 meteorites found in the Sahara and Antarctica. The main differences lie with the low-temperature (<200°C) releases of C; heavier C is released from the Antarctic finds. They also find no correlation between the amount of total C and terrestrial age. However, they did identify the main sources of contaminant C as arising from adsorbed air, biogenics, aerosols, and biocarbonates (all in the subaerial environment) and trapped air and clathrate hydrates in the subglacial environment. In summary, they found that the low-temperature C releases are dominated by site-specific contamination, and that this matter demands further in-depth studies.

P. Scherer discussed the role of weathering in the contamination of noble gases in meteorites. Terrestrial weathering alters the original noble gas contents, particularly in chondrites from hot desert regions. Concentrations of radiogenic and cosmogenic He and Ne are reduced in heavily weathered specimens, but high amounts of Kr and Xe from the terrestrial atmosphere are incorporated. The degree of weathering correlates roughly with the amount of these trapped gases, which are tightly bound. Elemental ratios of adsorbed atmospheric noble gases indicate that water might carry the gases into the meteoritic matter.

COSMOGENIC NUCLIDES

During the flight of meteoroids as meter-sized bodies in interplanetary space, the galactic cosmic ray particle irradiation produces stable and radioactive cosmogenic nuclides, which can be measured in the laboratory. From such measurements several important parameters of the history of the meteorites can be determined, such as exposure ages, size of the meteoroid, thermal history in space, pairing of specimens, and also the terrestrial age.

Antarctic meteorite finds are, in general, smaller in mass than those found in areas of more moderate climates, probably due to the relative ease of meteorite recognition on a white background. Thus, many of the Antarctic meteorites have suffered irradiation under lower shielding compared to modern falls and finds. This effect has not been studied very well, either experimentally or theoretically. R. Reedy and J. Masarik described results of calculations for the production rate of cosmogenic nuclides using a physical model that has been applied to meteorites of "normal" shielding conditions. They presented depth profiles of several relevant nuclides and nuclide ratios as a function of shielding depth and radius of the meteoroids. These figures can be used to interpret the measured data in small meteorites. Such calculations are also important for the determination of saturation activities of cosmogenic radionuclides, which are needed to calculate terrestrial ages. Furthermore, for small meteoroids the energetic solar particle irradiation may become important.

Three papers reported measurements of ^{10}Be and ^{26}Al in Antarctic meteorites and meteorites from hot deserts. These two isotopes have rather long half-lives compared to the terrestrial age from hot deserts meteorites and are thus not well suited for determinations of terrestrial ages. However, based on these measurements, pairing of specimens, geometries of meteoroids, and their exposure history can be obtained.

B. Melzow discussed measurements of these radionuclides in Saharan chondrites. Generally, ^{10}Be and ^{26}Al concentrations are well within the normal range of their respective class. Several pairings are indicated by similar concentrations of ^{10}Be and ^{26}Al and exposure histories of specific chondrites are discussed. U. Neupert reported radionuclide measurements, including ^{14}C, which is very well suited for terrestrial age determinations up to 30 k.y. These ages range for 13 Saharan chondrites from ~6 to 21 k.y. The interpretation of their measurements is based on production rates derived from physical model calculations.

Unusual exposure histories of some meteorites from the Lewis Cliff area are reported by K. Welten. For 85 meteorites, the ^{26}Al content, as well as that of K, is given. The distribution of ^{26}Al of Lewis Cliff chondrites shows a broad peak below the saturation value, indicating that many of these meteorites have terrestrial ages >100 k.y. The Lewis Cliff stranding zone might have been in operation longer than that of the Allan Hills, which is the oldest stranding surface thus far known. Several possible pairings are detected, and 85 specimens analyzed represent at least 47 individual falls.

TERRESTRIAL AGES

T. Jull and K. Nishiizumi compared the distributions of terrestrial ages from different hot deserts and individual Antarctic icefields. Such comparisons are vital for the understanding of concentration mechanisms, infall rates of meteoritic matter, and weathering processes. For chondrites from hot deserts ^{14}C is the most suitable nuclide for the determination of terrestrial ages because with this method ages up to about 40 k.y. can be determined. Most meteorites found in hot deserts fall into this age range. For meteorites with greater terrestrial ages, including many Antarctic meteorites, ^{36}Cl and ^{81}Kr are used, as well as ^{26}Al. Nishiizumi demonstrated that the measurement gap between ^{14}C ages (<40 k.y.) and ^{36}Cl ages (>70 k.y.) can probably be closed in the future by investigations of cosmogenic ^{41}Ca.

In the Libyan Desert, Algeria, and Roosevelt County (New Mexico, USA) the mean survival time of chondrites is >10 k.y. This is about a factor of 3 longer than the previously believed "weathering half-life" (about 3.6 k.y.) of ordinary chondrites typical of the climatic conditions of the western U.S. A correlation is found between terrestrial age and the weathering scale of Wlotzka et al. determined from a variety of weathering effects observed in thin sections. These weathering grades could replace the A-B-C classification of Antarctic meteorites, which is only a very qualitative scale of "rustiness."

The Nullarbor in Australia lacks very old specimens (T. Jull). This is in contrast to Roosevelt County where a very high proportion of "old" chondrites are found (some terrestrial ages >40 k.y. are observed). A "storage" of these meteorites in Pleistocene sediments over longer periods with lower weathering rates and a rather recent excavation is a possible explanation. The terrestrial ages of many Saharan Acfer meteorites are rather young (F. Wlotzka, U. Neupert); about 50% of these meteorites have terrestrial ages <10 k.y. A climatic change in the Sahara about 8 k.y. ago might be the reason for these small terrestrial ages.

Chondritic terrestrial ages from different Antarctic ice fields have different distributions. Very old meteorites (up to 1 m.y.) are found at the Main Ice Field of the Allan Hills area while chondrites found on other ice fields are younger. This has implications for the current explanation of the Allan Hills meteorite stranding surface and also shows that the Main Ice Field could be a much older feature than the ice fields to the west. A correlation of individual parts of the Lewis Cliff ice tongue with terrestrial ages of their meteorites is not observed (K. Nishiizumi), but K. Welten noted that this stranding surface might be older than that of the Allan Hills.

Nishiizumi also pointed out that no relationship is observed between terrestrial ages of chondrites and surface exposure ages of terrestrial rocks (determined from ^{10}Be and ^{26}Al in quartz) found in outcrops adjacent to the ice fields at the Allan Hills. Further investigations of this type are badly needed to better understand the concentration mechanism of meteorites at the Allan Hills.

For Antarctic meteorites no correlation is seen between terrestrial age and the currently used weathering categories (A, B, or C, gauged by rustiness). This is a puzzle, since it is generally believed that destruction by weathering is the main factor limiting terrestrial age.

R. Wieler reported noble gas and terrestrial age measurements on several chondrites from the Frontier Mountains. Values of all their measured samples are <140 k.y., and thus, lower than those from other Antarctic find locations. Also, among these meteorites pairings are detected.

D. Sears presented the record of thermoluminescence (TL) measurements on a large number of chondrites from hot and cold deserts. He noted that the natural TL is correlated with the terrestrial age for meteorites from hot deserts if a mean "storage" temperature of 20°C (Roosevelt County or western U.S. finds) and 30°C (Sahara) is taken. Assuming mean annual temperatures for the storage of Antarctic meteorites a "surface exposure age" as part of the terrestrial age is deduced. According to these TL measurements most of the meteorites spend <50% of their terrestrial history on the surface of the ice in Antarctica.

MECHANISMS AND CHALLENGES

During this session, two mechanisms of meteorite concentration and storage were presented, along with a case for acquiring martian sedimentary rocks as meteorites. In each case, a great amount of speculation was indulged in by the authors.

The question of how the physical parameters involved in Antarctic meteorite collection, transport, preservation, and concentration mechanisms works is still unresolved after 25 years of work. The general processes of ice movement, compressive flow, blockage, and specimen emergence from ice incorporation may fit most models, but these parameters also seem to differ from site to site. As the number of search areas expands, so do the questions regarding the processes involved in any one site.

The Allan Hills area has been the most studied and provides the longest-term measurements for surface movement and ablation. Unfortunately, the initial work in that area was fraught with measurement errors because the researchers were constrained to work without the benefit of sufficient absolute control. However, they did show that ablation rates over the ice surface were similar to those measured in the Yamato Ice Field and that surface ice movement decreased as the Allan Hills were approached. Within measurement constraints, the main ice field meteorite concentration area was judged to be in an equilibrium state. The general process of concentration was presumed to be the effect of compressive ice flow produced by the blocking effect of the Allan Hills coupled with a subglacial obstruction that forced bottom ice to the surface and carried encased meteorites with it. Ablation of the emerging ice by sublimation also appears to be a dominant force in the ice wasting process.

In a paper by G. Delisle, the author suggests that the field situation seen in Antarctica today is not typical for long-term meteorite storage. Computer models based on the response of the East Antarctic Ice Sheet to glacial stages show a different meteorite trap picture than originally presumed. His model shows that glacial stages result in thicker coastal ice, while interglacials produce thinner coastal ice. The consequences of this are seen in a change of velocity and mass transport of ice below the meteorite trap hinge line, which is at 2700 m elevation.

The case for Allan Hills is based upon the recovery of windblown meteorites that were suspected to have been buried and reemerged, as the interglacial sublimation rates are much higher than the glacial sublimation rates. This model certainly seems to support the idea that the Allan Hills ice originated at a point close to the meteorite trap as opposed to a catchment area further inland. Delisle also notes that a somewhat similar situation probably exists at the Frontier Mountain site. It will be most useful and interesting to see if future studies will support or refute his idea, especially since a catchment area location close to the meteorite traps will resolve the problem of length of transport of the emerging ice. In effect Delisle suggests that the meteorite traps are not stagnant regions but ones that respond differently to glacial and interglacial periods. Although Delisle has looked extensively at only a few sites in Victoria Land, it seems that his premise may augur well for a general concentration mechanism. To date, many researchers have noted that there may be regional differences among recovery sites located many kilometers apart. That may be true in one sense, such as a comparison between weathering and terrestrial age differences from one site to another. However, Delisle's general argument suggests that there may be no correlation between weathering and terrestrial age because some regions are closed systems and some are not. Whatever the case, Delisle's arguments present a new and intriguing point of view that deserves more research and serious consideration.

An important facet in the collection of meteorites is the size distribution of specimens. This distribution is related to many factors according to R. Harvey, who discussed a model related to wind movement, search efficiency, and fragment production. Harvey noted that in the supply of specimens there is an exponential increase in numbers per fragmentation event, which occurs prior to surface encounters. Hence the smaller the specimens the larger the total number. In addition he also considered weathering as a process that further fragments specimens once they reach the Earth's surface. Weathering occurs commonly with Antarctic meteorites and is even more pervasive (timely) among those fragments found in hot desert areas. Now that the smaller specimens are available it becomes necessary to relate size to both sorting and search efficiency as far as Antarctic finds are concerned. Eolian effects are most pronounced in Antarctica and simulations have shown that specimen size is inversely proportional to specimen movement. The mass threshold is a function of wind velocity, which relates to a specific area and may not be the same over different search regions. As noted by Harvey, search efficiency is also important but in general is related strongly to particle size, even though other factors such as visual acuity and terrain are considered. It has been the experience of many that wind direction during search plays a significant role, i.e., fewer meteorites are spotted as you travel into the wind. The result of his study shows that an optimum size distribution of finds ranges between 2 and 64 g with a peak recovery mass around 8–10 g. The fall-off in the smaller range is related to loss mechanisms and that in the larger range to supply numbers and breakage sizes. Regardless of the parameters it does seem prudent to assume that careful foot searching in areas of eolian traps will yield large numbers of specimens. This effect may skew the results of this model to the smaller mass but nevertheless increases the chances of a searcher finding the rare jewels. It would be best if all searches could be done so thoroughly, but this also requires the additional constraints of time and personnel. Given the complexity of Antarctic logistics and funding constraints it seems best to live with what can be accomplished within reasonable limits.

The problems related to collecting efficiency of Antarctic meteorites are further exacerbated if what is found is not recognized as a meteorite. In a paper given by I. Wright this particular dilemma is addressed as it would pertain to sedimentary rocks from Mars. Martian samples presently in collections are SNC types of volcanic origin that are basically examples of shallow intrusive or extrusive basaltic rocks. The evidence from Viking landers and orbiters suggests that the martian surface has experienced widespread fluvial activity in the past. These results suggest the possibility that sedimentary deposits could exist close to the surface. Wright suggests that an impact event capable of ejecting SNC meteorites might also eject carbonate rocks. The problem, then, is that even experienced meteoriticists might fail to recognize them because they would probably lack or have an unusual fusion crust.

The Antarctic is probably the best place to search for these samples since the preservation factor is so high. To get over the problem of sample recognition, Wright proposed that all the rocks in an area be collected and screened. In the light of time and budget constraints this hardly seems feasible at the present time. On the other hand, if we develop low-mass highly portable mass spectrometers capable of *in situ* realtime analysis, this could solve the field problem.

DIFFERENT POPULATIONS?

A very contentious subject of prior workshops has been that of potential compositional and mineralogical differences between younger finds and falls vs. older finds. In fact the previous workshop was entirely devoted to this subject, and the controversies continued at this workshop. In general, it appears that the important issue of possible observed changes in the H chondrite populations remains unresolved.

In the first of two papers, S. Wolf and M. E. Lipschutz continued to argue that there is chemical evidence that Antarctic H4–6 and L4–6 chondrites with terrestrial ages >50 k.y. (from Victoria Land) are different from those that are younger (Queen Maud Land meteorites and modern falls). A difference between these meteorites would imply a change in the sources providing these meteorites over a timescale deemed too rapid by many dynamicists. Since the last Antarctic meteorite workshop these workers have increased the sophistication of their principal component and linear discriminant statistical analyses of 10 volatile trace elements. Wolf and Lipschutz argue that they have properly avoided sampling and analytical bias and the effects of sample pairing in their analyses. They point to supporting evidence provided by P. Benoit and D. Sears. Critics continue to suggest that weathering may have redistributed the volatile trace elements being used for the arguments. Other critics point out that if it takes statistical examination of fully 10 trace elements in order to see a difference between the putative meteorite groups, then they are really more alike than unlike. Critics also suggest that the sudden change in ordinary chondrite source material indicated by Wolf and Lipschutz's results is dynamically unlikely.

In their second paper, Wolf contended that short-period variations in the record of H chondrite falls have been documented in a recent paper by themselves and R. Dodd, and they ascribe these to meteorite streams associated with Earth-crossing asteroids. At the workshop, Lipschutz suggested that the Shoemaker-Levy 9 comet chain may serve as a good illustration of meteorite streams. However, the lifetime of the former was just 18 months, not the thousands of years required to explain the longer-period changes they report in their first paper (see immediately above).

In a test of the Lipschutz-Wolf model, Loeken performed analyses of noble gases in H chondrites from Antarctica (from the Allan Hills and the Yamato Mountains) and modern falls. The authors were careful to select only Antarctic meteorites analyzed by Wolf and Lipschutz. They find no correlation between terrestrial age and either exposure age, radiogenic ^{4}He, or radiogenic ^{40}Ar over the period of the last 200 k.y. One would expect to see such correlations if the population source for Antarctic H chondrite finds and modern H chondrite falls indeed differed.

D. Sears next described a grouping of H-chondrite Antarctic finds not represented among modern falls, which they have grouped together due to high induced TL peak temperature, high calculated metallographic cooling rates, and relatively high ^{26}Al activities. They call these "rapidly cooled" H chondrites. Since all examples of this group have relatively high terrestrial ages (>40 k.y.), they suggest that they could correspond to the older of the chemical groupings proposed by Wolf and Lipschutz. However, in contrast to the results of Wolf and Lipschutz, they find a mixture of "normal" and "rapidly cooled" H chondrites with terrestrial ages in excess of 40 k.y. They indicated regret that none of these unusual H chondrites had been analyzed by Loeken and Schultz.

FUTURE PLANS

This session was an opportunity for the major players in the meteorite recovery game to talk about their plans for the future. Although many plans appear firm, some of those involving hot deserts are fraught with political problems. Interested persons should contact the specific personnel involved to ensure that the projected plans presented here have not changed.

EUROMET (C. Pillinger): EUROMET was created as a vehicle for European meteoriticists to cooperate as a unit. It includes a number of different agencies and museums throughout Europe, but remains the single coordinating body and the center for the curation and identification of recovered specimens. Some funds are and have been available for hot desert searches plus work on cosmic dust and micrometeorites recovered from polar ice. At the present time, EUROMET helps sponsor Antarctic expeditions as well. Future sites for continued work are the Frontier Mountains, Antarctica, and the Nullarbor Plain in Western Australia.

Some specifics on the above-mentioned sites and others are as follows:

The Takla Makan Desert. This is a cooperative reconnaissance effort between R. Hutchison, British Museum, and the Chinese government. The first expedition failed to produce any meteorites. If future ventures are productive, EUROMET will become involved.

Nullarbor Plain. L. Schultz, Max-Planck-Institut, Mainz, is the coordinator for this expedition and so all interested persons should contact him. A. Bevan from Perth will also coordinate this effort from the Australian side. This site has been an area of high productivity in the past and so future expectations are high.

The Middle East. The primary search area is Oman, where there are some environmentally sensitive areas that interest meteoriticists. EUROMET intends to return some day but the exact dates are tentative at the present time.

North Africa. North Africa, especially Algeria and Libya, are proven regions for meteorites, but at the present time the political situation makes an expedition impossible. In 1995 there will be a British expedition that will cross the Sahara Desert. They have agreed to include one person who will survey the route for meteorites and possibly establish a refueling site for a future search party. EUROMET will probably contact Libyan officials for permission to form a search expedition at some later date.

Antartica. Antarctic plans for EUROMET are coordinated generally by G. Delisle. There will be two areas of interest in the 1995–1996 field season, namely Queen Maud Land and Frontier Mountain/Outpost Nunatak. Queen Maud Land is the site of an old East German station that will be visited and from there meteorite searches will be conducted.

ANSMET (U.S.) (R. Harvey): The U.S. program is presently funded for two more collection years. The plans for the funding years are as follows:

1994–1995. The team returned to the Foggy Bottom site at the Lewis Cliff area for a complete search. A short two-week reconnaissance trip utilizing Twin Otter support is also planned for the Byrd and Darwin Glacier areas. There are large blue ice areas in these regions but their potential for meteorite recovery needs to be determined.

1995–1996. Things are a bit undecided at present but this may turn out to be a season of extended reconnaissance efforts. A summer camp is planned for extensive activities by the National Science Foundation on the plateau side of the Shackleton Glacier. This could be an ideal location for searching many possible sites and for planning future activities.

Long-term plans are tentative, but are necessary for future funding. Harvey hopes to expand the work beyond just meteorite recovery and focus somewhat upon ice flow problems. Emphasis will be placed upon chemistry, exposure history, network triangulation systems, and drainage system studies. Regions of interest for future searches include the Pecora Escarpment (LaPaz Ice Field), inland of the Amery Ice Shelf near the pole of inaccessibility, and the Lambert Glacier. The last two regions would require some type of cooperation with the Australian National Antarctic Expedition (ANARE). Talks have been held with ANARE in the past and will continue in the future. Unfortunately, not only are logistics a problem, but funding is also because ANARE cannot afford to support a large U.S. team just to search for meteorites.

Other long-term tentative plans in the future involve the Weddell Sea area and collaboration with glaciologists. K. Eschelmeyer has expressed some interest in obtaining a grant for student research on blue ice fields. Regardless of the plans, Harvey commented that the future of the program and field time is strongly dependent upon the success of the reconnaissance activities.

NIPR Japan (H. Kojima): The National Institute for Polar Research (NIPR) has not been very active in meteorite searches during the last five years. The problem is a common one: funding many programs with a somewhat dwindling supply of financial support. The five-year plan for 1996–2000 will include a meteorite search that will concentrate efforts in Yamato, Belgica, and the Sør Rondane Mountains. The difficulty is that the meteorite party must spend the winter at Syowa Base and travel during the summer season on oversnow vehicles to the search areas. The general plan is to travel by ice breaker to Syowa base in December 1997, do cosmic dust collection experiments during the winter-over, travel to the Yamato Ice field in October 1998, and search the Yamato and

Belgica area in November and December. In January 1999 the party will return to Syowa Base and take the ice breaker back to Japan.

Namib Desert (A. Reid): Reid and associates are planning to return to this region during the spring of 1995. All arrangements have been made for the work except for the funding of the expedition. All specimens found will be cut in Namibia and half left there. Those specimens taken to the U.S. for examination will also be returned to Namibia, minus what amounts are used in scientific studies.

Reid also mentioned that he and others hope to return to the Atacama Desert in north Chili. No special time frame was given for that return.

Tibetan, Plateau Cocosili Area, China (N. Takaoka): Takaoka has reported that no meteorites were found in this area of China. The area is very high (4500–5000 m) and covered with pebbles and fine sand. The region shows evidence of spring fluvial activity but no running water was found during the search.

Repositories of Desert Meteorites

At present, meteorites collected in Antarctica, Roosevelt County, NM, Northern Africa, Australia, and Southern Arabia can be obtained by qualified investigators. The information below is provided to facilitate these loans.

ANSMET

Antarctic meteorite samples collected in the course of the Antarctic Search for Meteorites (ANSMET) expeditions are available to research scientists of all countries, regardless of their current state of funding for meteorite studies. These expeditions result from a unique agreement between the National Science Foundation (NSF), the Smithsonian Institution, and NASA. In this arrangement the NSF provides the funding and support for collection activities, and NASA and the Smithsonian provide the curatorial and meteorite expertise. Meteorite recovery expeditions have been held on generally a yearly basis since 1976. The localities visited in this time are given in Fig. 1 and Table 1.

Samples collected by these expeditions are available through the Meteorite Working Group (MWG). The MWG is a peer-review committee that meets twice a year to guide the collection, curation, allocation, and distribution of the U.S. collection of Antarctic meteorites. Issuance of samples does not imply a commitment by any agency to fund the proposed research. Requests for financial support must be submitted separately to the appropriate funding agencies. As a matter of policy, ANSMET meteorites are the property of the NSF, and are considered loans subject to recall.

Each request should accurately refer to meteorite samples by their respective identification numbers and should provide detailed scientific justification for proposed research. Specific requirements for samples, such as sizes or weights, particular locations (if applicable) within individual specimens, or special handling or shipping procedures should be explained in each request. Requests for thin sections that will be used in destructive procedures such as ion probe, etch, or even repolishing, must be stated explicitly. Consortium requests should be initialed or countersigned by a member of each group in the consortium. All necessary information should probably be condensable into a one- or two-page letter, although informative attachments (reprints of publications that explain rationale, flow diagrams for analyses, etc.) are welcome. Requests should be sent to

Secretary
Meteorite Working Group
Mail Code SN2
NASA Johnson Space Center
Houston TX 77058
USA

NIPR

The National Institute for Polar Research (NIPR) in Tokyo has successfully managed numerous meteorite collection expeditions to the Antarctic, including the first (!), and collected thousands of meteorite fragments in the process. These searches have occurred since 1973 in the Yamato, Belgica, and Sør Rondane Mountains (the latter including the Asuka specimens). Information on many of these meteorites has been published in *Meteorite News* (published by the NIPR), and the abstracts and papers resulting from the annual Symposium on Antarctic Meteorites, hosted by the NIPR. These Antarctic meteorites are the property of the NIPR, and loans are generally made for a period of one to two years.

All requests for meteorite samples are reviewed by the Committee on Antarctic Meteorites, which meets approximately twice a year. Each request should accurately refer to meteorite samples by their respective identification numbers and should provide detailed scientific justification for proposed research. Specific requirements for samples, such as sizes or weights, particular locations (if applicable) within individual specimens, or special handling or shipping procedures should be explained in each request. Requests for samples or thin sections that will be used in destructive procedures such as ion probe, etch, or even repolishing, must be stated explicitly. Allocations of very tiny individuals, or samples of more than 10 different meteorites at any one time may not be honored.

Requests for meteorite samples and additional information should be addressed to

Dr. Hideyasu Kojima
Curator of Meteorites
Department of Antarctic Meteorites
National Institute of Polar Research
9-10, Kaga 1-chome, Itabashi-ku
Tokyo 173
JAPAN

EUROMET

There have been several European Search for Meteorites (EUROMET) expeditions to Antarctica, generally held within the larger framework of German (GANOVEX) and Italian (PNRA) national Antarctic programs. The Allan Hills was visited during the 1988–1989 field season and the Frontier Mountains, in North Victoria Land, were visited during the 1990–1991 and 1993–1994 expeditions. In 1993 a EUROMET expedition collected meteorites in southern Arabia, and plans are being made for visits to other hot deserts. Four joint EUROMET/WAMET expeditions to the Nullarbor Plain have taken place since spring of 1992.

Preliminary descriptions of EUROMET meteorites are published in the *Meteoritical Bulletin* as soon as possible. All allocations are considered loans. Each request should accurately refer to meteorite samples by their respective identification numbers and should provide detailed scientific justification for proposed research. Specific requirements for samples, such as sizes or weights, particular locations (if applicable) within individual specimens, or special handling or shipping procedures should be explained in each request. Requests for samples or thin sections that will be used in destructive procedures such as ion probe, etch, or even repolishing, must be stated explicitly.

Requests for meteorite samples and additional information should be addressed to

Dr. Robert Hutchison
Department of Mineralogy
The Natural History Museum
Cromwell Road
London SW7 5BD
UK

WAMET

For the past decade Prof. A. Bevan has led numerous expeditions through the Nullarbor Plain in Western Australia, recovering thousands of meteorite fragments. EUROMET has participated in several of the most recent recovery expeditions.

The disposition of Western Australian meteorites is controlled by the Meteorite Commission of Western Australia, which arranges for peer review of all requests. The WAMET meteorites are the property of the Western Australian Museum, and all allocations are considered loans. Each request should accurately refer to meteorite samples by their respective identification numbers and should provide detailed scientific justification for proposed research. Specific requirements for samples, such as sizes or weights, particular locations (if applicable) within individual specimens, or special handling or shipping procedures should be explained in each request. Requests for samples or thin sections that will be used in destructive procedures such as ion probe, etch, or even repolishing, must be stated explicitly.

Information on these collections and the availability of samples can be obtained from

Prof. Alex Bevan
Department of Mineralogy
Western Australian Museum
Francis Street
Perth, Western Australia 6000
AUSTRALIA

MISCELLANEOUS COLLECTIONS

Many North African desert meteorite finds are in the collections of Dr. D. Weber, Institut für Planetologie der Universität, Münster, Germany; Dr. F. Wlotzka, Max-Planck-Institut für Chemie, Mainz, Germany; Dr. K. Metzler Museum für Naturkunde der Humboldt-Universität, Berlin, Germany; and Prof. C. T. Pillinger, Open University, Milton Keynes, UK.

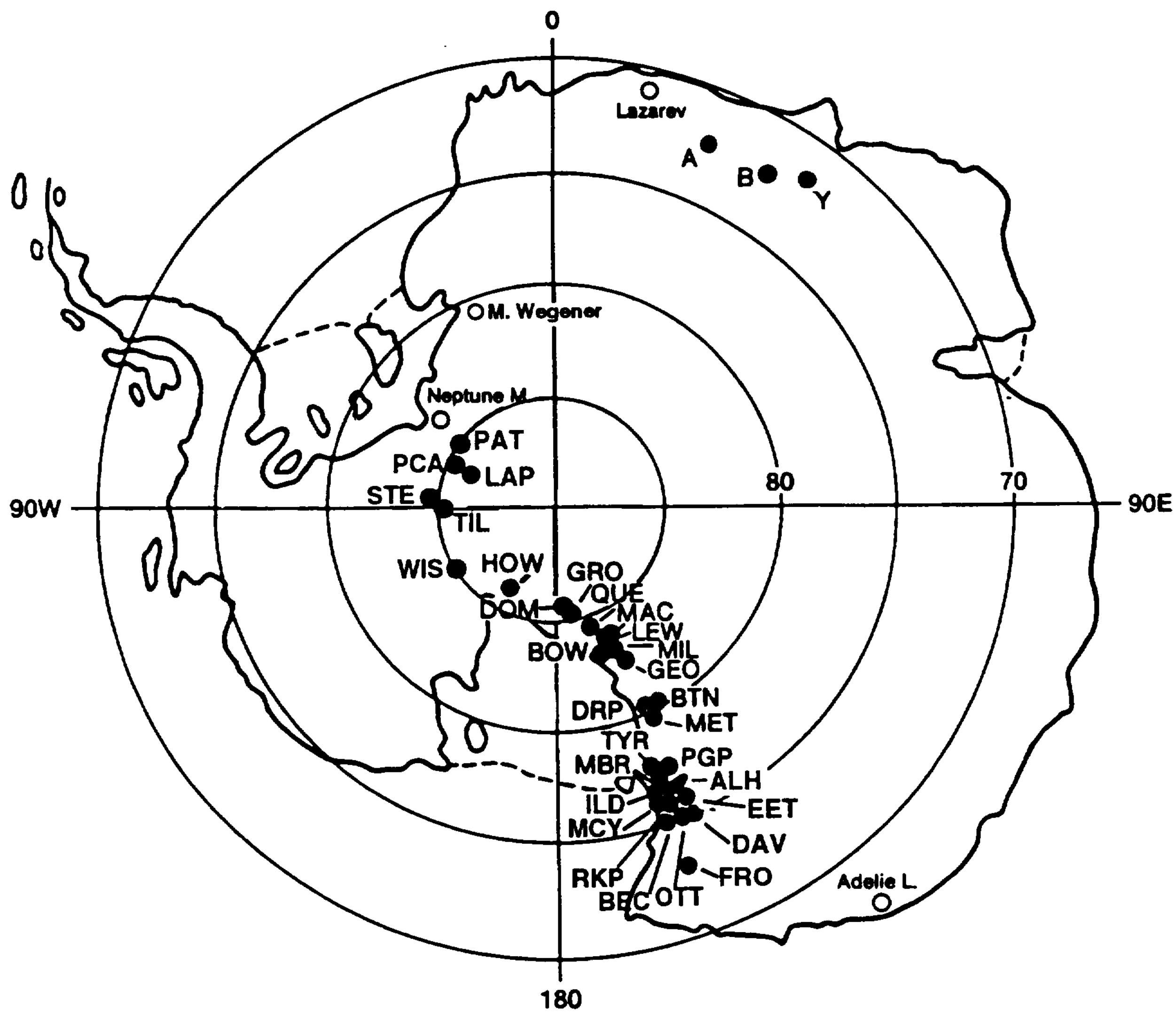

Fig. 1. Antarctic meteorite locations.

A	—	Sør Rondane Mountains (Asuka)	MBR	—	Mount Baldr
ALH	—	Allan Hills	MET	—	Meteorite Hills
B	—	Belgica Mountains	MIL	—	Miller Range
BOW	—	Bowden Neve	OTT	—	Outpost Nunatak
BTN	—	Bates Nunataks	QUE	—	Queen Alexandra Range
DOM	—	Dominion Range	PAT	—	Patuxent Range
DRP	—	Derrick Peak	PCA	—	Pecora Escarpment
EET	—	Elephant Moraine	PGP	—	Purgatory Peak
GEO	—	Geologists Range	RKP	—	Reckling Peak
GRO	—	Grosvenor Mountains	STE	—	Stewart Hills
HOW	—	Mt. Howe	TIL	—	Thiel Mountains
ILD	—	Inland Forts	TYR	—	Taylor Glacier
LAP	—	LaPaz Ice Field	WIS	—	Wisconsin Range
LEW	—	Lewis Cliff	Y	—	Yamato Mountains
MAC	—	MacAlpine Hills			

Abstracts

THE FATE OF METEORITIC CARBON IN HOT AND COLD DESERTS. R. D. Ash[1] and C. T. Pillinger[2], [1]Department of Geology, University of Manchester, Oxford Road, Manchester M13 9PL, UK, [2]Planetary Sciences Unit, Department of Earth Sciences, Open University, Milton Keynes MK7 6AA, UK.

Introduction: As a result of the large influx of meteorites into laboratories from hot and cold deserts, many previously rare meteorites are becoming more available for study, and new and unique meteorites have been recovered. Although the samples recovered often show remarkably little weathering considering their terrestrial ages, they are not pristine and both mineralogical changes and oxidation are ubiquitous. The chemical changes show variation between localities; for example, halogens appear depleted in the Sahara [1], but are commonly enriched in the Antarctic [2]. Many other elements show similar variations with enrichments in some deserts, depletions in others.

In this paper we review the effects of long terrestrial residence times on C contents and occurrence of meteorites from three desert localities: the cold deserts of Antarctica, the semiarid region of Roosevelt County, USA, and the hot desert of the Sahara, North Africa. The form of preservation and the climate play important roles in the style of weathering and the potential contaminant species. In the Antarctic the meteorites have been preserved in the ice but also spend considerable time on meteorite stranding surfaces, in the Sahara meteorites reside on the surface of limestone plateaus, and in Roosevelt County meteorites have been preserved by burial in sand and soil and subsequent uncovering by wind ablation.

The two most common forms of C in meteorites are organics and carbonates, both of which are also present in high abundances on the surface of the Earth, which leads to potential problems with contamination. Other minor carbonaceous components, such as presolar materials (diamond, graphite, SiC), appear unaffected by residence in deserts.

Falls and Finds: The first studies of the effects of terrestrial residence on C were carried out on whole-rock samples using bulk techniques. Early work on the C abundances of ordinary chondrites showed that there was no difference in the median values for falls and finds of the H- and L-group chondrites [3]. However, if the mean values of the L and LL groups from this study are considered, there is a twofold depletion in the C contents of the finds over falls, something observed in all petrologic grades. The falls in this study were not selected from any particular environment, but the majority of the finds were from the farmlands of the midwest U.S., so they had generally been subject to burial in prairie land soil.

A later study of several specimens of the meteorite Holbrook, which had been collected at various times after its fall (in 1912), was conducted, and a threefold increase in C content was found between samples collected immediately after the fall (517 ppm) and one collected 19 years later (1560 ppm). However, the weathering effects appear to be variable, as a sample collected 37 years later had an intermediate C content (1125 ppm) [4]. Neither of these studies determined the isotopic compositions of the C nor the nature of the material lost or gained.

Later studies of ordinary chondrites have included data on C

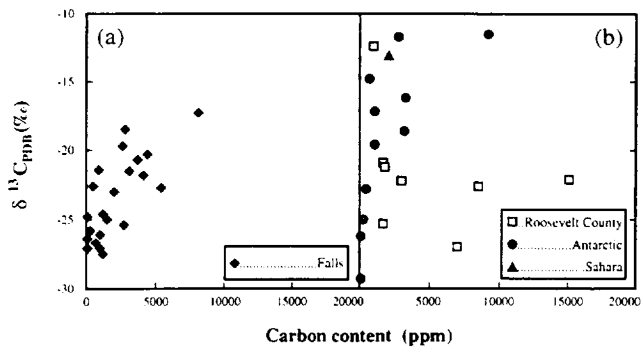

Fig. 1. A comparison of the C content and isotopic composition of (a) ordinary chondrite falls and (b) ordinary chondrite finds. (Additional data from [7,18,19].)

contents and isotopic compositions (Fig. 1). This has made the identification of weathered materials and introduced species easier. It has been found that the effects of weathering on ordinary chondrites tend to increase the C content, but for different reasons.

Organics: The C budget of primitive chondrites is dominated by a macromolecular, highly insoluble organic material. This constitutes up to 90% of C in carbonaceous chondrites, contributing less to metamorphosed carbonaceous and ordinary chondrites, where graphitic material becomes dominant.

The organic material found in carbonaceous chondrites is severely affected by the conditions found in the hot deserts of the Sahara. The temperature of the meteorites on the desert floor (>80°C [5]) is high enough for the destruction of the macromolecular material, probably by a process akin to catalytic hydrolysis. These reactions are enhanced by the presence of alkali groundwaters and involves the cleaving of C-C bonds in the macromolecular organic material to produce soluble and/or volatile organics that are then lost to the environment. The Saharan carbonaceous chondrites show up to 80% loss of their organic C content compared with other, non-Saharan members of the group. Carbonaceous chondrites that have undergone more parent body heating, such as the C3s, show less C depletion than the lower-temperature chondrites due to the greater resistance to degradation through weathering due to their more graphitic nature [6].

Unlike the surface preservation of meteorites in the Sahara, meteorites from the semiarid region of Roosevelt County (New Mexico and West Texas) have spent the majority of their terrestrial residence buried in the soil. The result of this is that they have gained organic C [7], and the longer the terrestrial residence, the more weathered the samples become [8] and the more C-rich the meteorites become (Fig. 2). The meteorite of weathering grade C with the high C content is Roosevelt County 075 (see below). For simplicity the high indigenous C content has been subtracted from the total, leaving just the C attributable to weathering. This C can be separated analytically from the indigenous, meteoritic C by stepped combustion, with the terrestrial material combusting before the meteoritic carbonaceous compounds. This was carried out on the primitive H chondrite Roosevelt County 075, which has the highest C content of any ordinary chondrite of ~1.5%. Using stepped combustion it was found that more than half the C in this sample has a

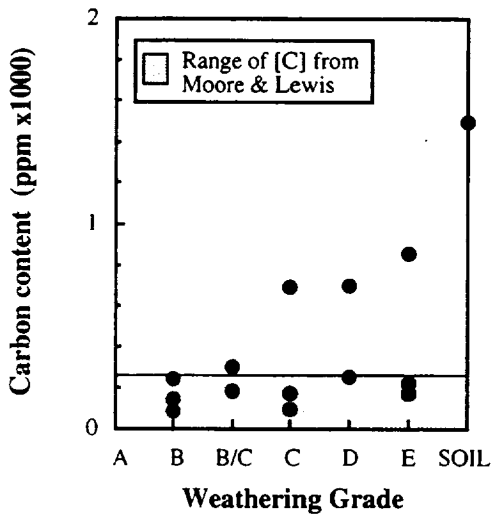

Fig. 2. The C content of Roosevelt County ordinary chondrites of known weathering grade (from [7,9]).

terrestrial origin, with a $\delta^{13}C$ of ~ -25‰ [9]. This is the typical isotopic composition for terrestrial plant matter (range -24‰ to -34‰ [10]) and for recent sediments (range -20‰ to -27‰ [11]). There is no evidence for any destruction of the meteoritic carbonaceous material, although the absence of any carbonaceous chondrites from Roosevelt County makes this difficult to assess, but the organic material from Roosevelt County 075 appears isotopically unchanged.

Analyses of Antarctic chondrites indicate that the organic materials are unaffected by their residence in the polar ice. Stepped combustion shows that there is some increase in the lowest-temperature material (see below and [12]) but that the organic peak in the combustion remains isotopically and quantitatively indistinguishable from observed falls.

Carbonates: Carbonaceous chondrites contain up to 5400 ppm indigenous carbonate. It is formed by parent-body hydrothermal processes and is generally isotopically distinct from terrestrial material, being isotopically heavy with $\delta^{13}C$ values up to 81‰ [13]. Although seemingly absent from ordinary and enstatite chondrites, carbonates are also present in the SNC meteorites as a martian weathering product or hydrothermal deposit.

Carbonaceous chondrites from the Sahara show evidence for the precipitation of up to 10,000 ppm carbonate. This has been shown to be entirely calcitic in composition [14], whereas all the magnesian carbonate in the meteorites has an isotopic composition commensurate with an extraterrestrial origin. The calcium carbonate is introduced by groundwater that is carbonate rich from percolation through limestones before being drawn into the meteorite by osmosis. The evaporation of the water leads to the deposition of carbonates in veins commonly associated with other weathering features, such as FeO deposits. This is potentially a powerful tool for the destruction of meteorites in the desert environment.

In the cold deserts of Antarctica the deposition of evaporitic carbonate takes place to a lesser extent and is of different composition. The majority of the cold desert deposits are hydrated carbonates, such as nesquehonite and hydromagnesite [15]. These have a

TABLE 1. Carbonaceous components and characteristics of desert meteorites

	$\delta^{13}C$ (‰)	T_c (°C)	ENV. H	C	SA
Low T	~0	<250	+	+	+
Organic	-25	<400	–		±
Carbonate	0	600–700	+	+	+

+ material gained; – material lost; T_c is temperature of combustion; ENV is environment, where H = hot desert, c = cold desert, SA = semi-arid.

C isotopic composition of ~1‰ and are believed to have been formed from a mixture of atmospheric CO_2 and CO_2 dissolved in ice water [16]. Carbonates of terrestrial origin are also found in the SNC meteorites [17].

Despite the preservation within sands, which are believed to have been at some stage cemented with a calcareous cement [18], the meteorites of Roosevelt County appear to have escaped carbonate contamination. Stepped heating of Roosevelt County 075, the meteorite from this region most affected by organic contamination, shows that the amount of C yielded over the carbonate decomposition range (600°–700°C) is equivalent to less than 500 ppm calcite. Visual inspection of some samples from the Nullarbor Plain, western Australia, shows evidence for the presence of carbonates from this semiarid limestone environment.

Low-Temperature Carbon: The presence of high C yields at low temperatures (<250°C) in the stepped combustion analyses were first noted in Antarctic ordinary chondrites [19]. The composition of this material was found to be isotopically heavy with respect to the bulk meteorite, with $\delta^{13}C$ values up to 0‰. Analysis of other chondritic meteorites from the Antarctic have shown similar effects, as have meteorites from the Sahara and Roosevelt County. A more detailed study has been undertaken that has shown possible geographical dependence of the degree of low-temperature contamination in the Antarctic, and it has been suggested that it may be connected with aerosol sea spray [12].

Conclusions: The C content and composition of meteorite finds from both hot and cold deserts is affected by the environment in which they are found (for a summary, see Table 1). Thus care must be taken when interpreting C data, particularly from bulk whole-rock samples from these regions. Some effects, such as the organic contamination encountered in Roosevelt County meteorites, can be overcome by the application of suitable analytical techniques, e.g., stepped combustion. Other problems, such as the loss of organic material from hot desert samples and the growth of carbonates in Saharan and Antarctic samples, at present appear more intractable.

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TERRESTRIAL AGE CLUSTERING OF METEORITE FINDS FROM SITES IN ANTARCTICA AND HOT DESERTS. P. H. Benoit and D. W. G. Sears, Cosmochemistry Group, Department of Chemistry and Biochemistry, University of Arkansas, Fayetteville AR 72701, USA.

Many concentrations of meteorite finds have been found in hot and cold desert regions of the world. The sites include the deserts of northern Africa, the western U.S., and Australia, in addition to the ice fields of Antarctica [1–3]. These large groups of meteorite finds allow detailed study of the nature of the meteorite flux in the prehistorical past [e.g., 4,5]. In this paper we discuss terrestrial age data, derived from cosmogenic radionuclide abundances (such as ^{14}C and ^{36}Cl), and natural thermoluminescence data for meteorite finds from sites in both hot and cold desert sites. We find that at all the sites we have examined to date there is distinct clustering of either terrestrial ages or surface exposure ages of the meteorite finds; we suggest that meteorite concentration in hot and cold deserts is generally episodic, reflecting changes in regional climate or changes in local conditions such as directions of ice or stream flow over time.

The natural thermoluminescence (TL) level of a meteorite find is determined by radiation dose, temperature, and time. At a given temperature, the equilibrium natural TL level of a meteorite is directly proportional to the dose rate. Since the radiation dose rate for meteorite finds is inevitably far less than during irradiation in space, the natural TL level of a meteorite on Earth will decrease over time until a new, much lower equilibrium level is reached, this level being determined by terrestrial temperature and radiation dose. At equilibrium, higher temperatures result in lower natural TL levels. Under nonequilibrium conditions, the rate of TL decay is determined by temperature. The systematics of natural TL decay in ordinary chondrites have been detailed by theoretical calculations and laboratory heating experiments [6], and comparisons have been made with terrestrial age estimates obtained using cosmogenic radionuclide abundances [7,8]. However, the latter comparison makes the assumption that meteorite finds have one-stage terrestrial thermal histories, which is not necessarily the case for Antarctic meteorites. In fact, TL results can be particularly interesting in cases where the meteorites have experienced discrete multistage terrestrial thermal histories.

The TL methodology and data reduction techniques have been discussed elsewhere [e.g., 8,9]. Depth effects, which are common problems in cosmogenic nuclide studies, are not a significant factor in governing natural TL levels except for the largest meteorites [10]. In the present study we limit our database to ordinary chondrites of type 3.7 and higher, which are thought to have the same major TL phosphor. It is possible to compare TL data for achondrites with those of ordinary chondrites, but corrections must be made for "anomalous fading" [9].

Roosevelt County/Western U.S.: In Fig. 1 we compare our TL data with the ^{14}C-derived terrestrial ages for meteorite finds from the western U.S. We show in Fig. 1a the 1980 version of this plot, where ^{14}C terrestrial ages were obtained by Boeckl by β counting [11], and in Fig. 1b we show the current version, where ^{14}C terrestrial ages are from Jull's AMS data [12]. Apparently, between 1980 and 1990, TL data were providing more reliable information on meteorite terrestrial ages than ^{14}C data and there was a misplaced confidence in ^{14}C-derived terrestrial ages. Natural TL decay curves for various "storage temperatures" are also shown on Fig. 1b. In general, the meteorites plot close to the 20°C TL decay line. From data for finds from the western U.S. (Fig. 1b) it is apparent that most of these meteorites have fairly short terrestrial ages, with most having terrestrial ages <5 k.y. There are few meteorites with terrestrial ages between ~5 and 30 k.y., and even fewer with ages >30 k.y. This distribution is very different from that of the Roosevelt County meteorite finds (Fig. 2; ^{14}C data from [13]), in which only a very few meteorites have terrestrial ages <5 k.y. and all other meteorites have terrestrial ages >20 k.y. In both databases there are a few meteorites (Ladder Creek and Roosevelt County 064) with TL levels far lower than that expected in consideration of their ^{14}C-derived terrestrial ages; these meteorites were probably reheated in space prior to Earth impact [14].

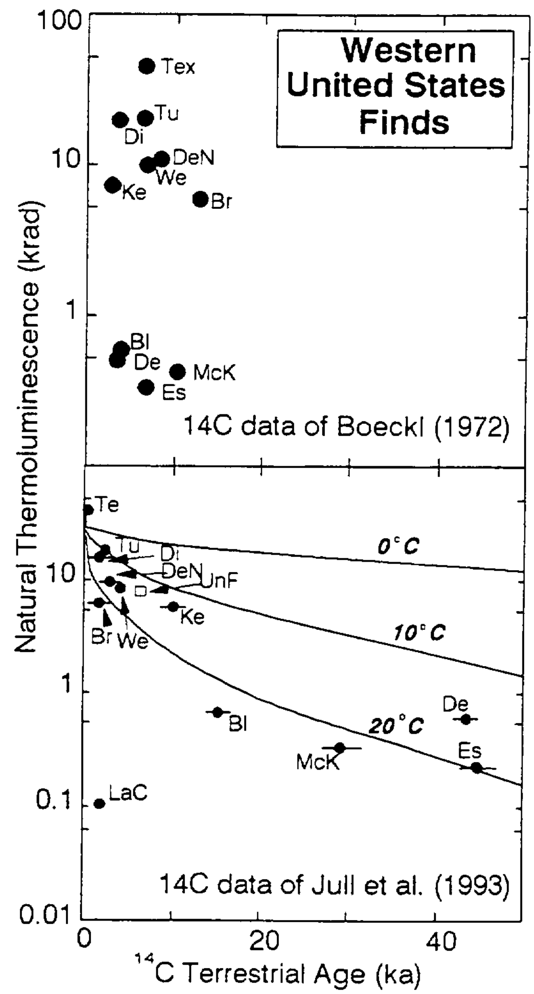

Fig. 1. Western U.S. finds.

The difference in age distributions between these two collections almost certainly reflects differences in collection and recovery

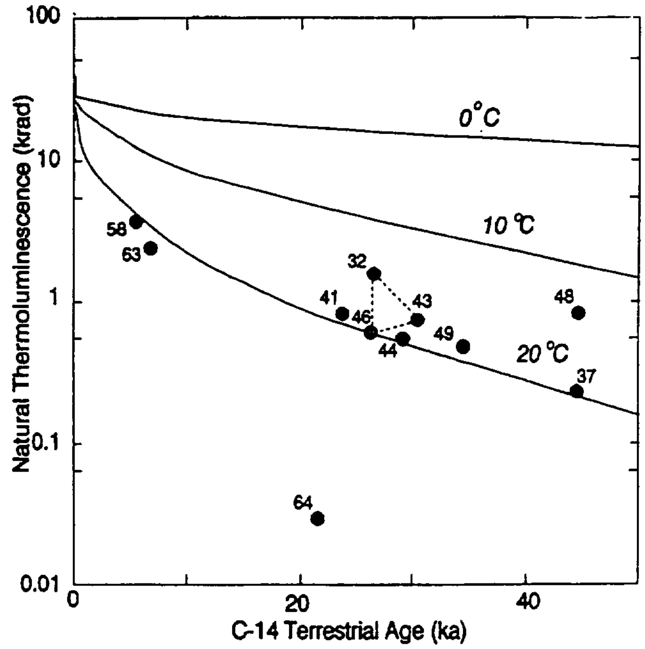

Fig. 2. Roosevelt County meteorites.

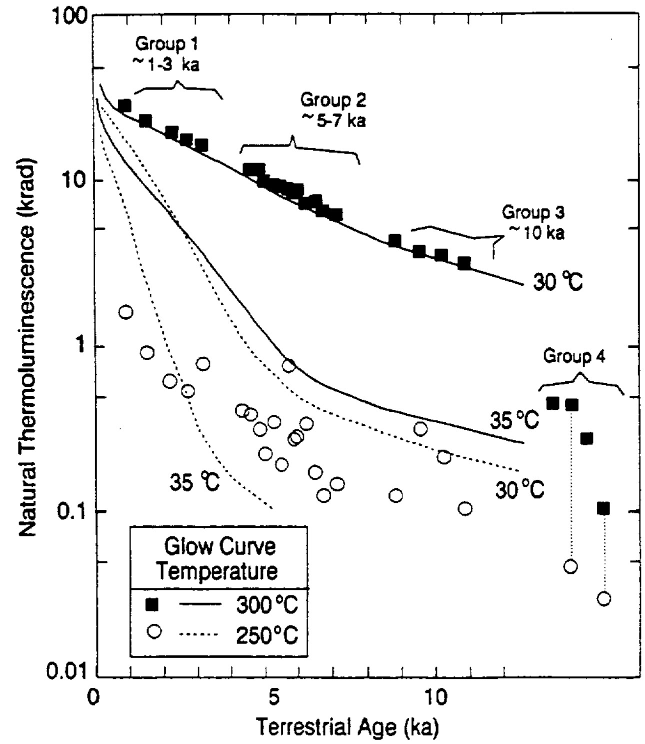

Fig. 3. Saharan meteorites.

history. The Roosevelt County samples are from highly localized blow-outs that were systematically searched, while the western U.S. finds are chance discoveries over an ≈800-km region. However, it is interesting that in both databases there is a fairly distinct gap between ~10 and 20 k.y. in which few meteorites are found. Jull et al. [12] suggested that the Roosevelt County distribution was produced by the loss of meteorites in the intermediate age range during the blow-out events. This interpretation seems reasonable because of the small size of these meteorites (generally <100 g). However, the western U.S. finds are generally >2 kg and occasionally >100 kg. The only meteorite that has an age in the 10–20-k.y. range is the L6 chondrite Bluff, which is especially large (142 kg). One possible conclusion from this is that between ~10 and 20 k.y. ago, conditions were unsuitable for meteorite accumulation/preservation over most of the western U.S. and that a regional variable, such as an unfavorable climate, was responsible for loss of most meteorites in the gap.

North Africa: A plot of ^{14}C-derived terrestrial ages [2] vs. natural TL data for a fairly small group of finds from Daraj, Libya, looks similar to the equivalent plot for finds from the western U.S. (Fig. 1b), although the meteorites tend to plot along a TL decay curve for a storage temperature of 30°C instead of 20°C (see [8]). If we plot our TL data for meteorite finds from the Acfer, Hammadah al Hamra, Ilafegh, Reggane, and Tanezrouft sites along this curve (^{14}C data are not available for these meteorites) we find that there are four distinct groups (Fig. 3). Three of the groups appear to reflect the terrestrial age distribution, whereas the fourth probably consists of reheated meteorites, which most likely have had their TL drained in small perihelia orbits. North Africa has had a complex climate history over the last 15 k.y., but it appears that the area was much wetter in the past and fluvial processes were especially active at about 10,000 and 5100 BP, at least in some portions of the current Sahara desert [15]. It thus appears that, as suggested by Jull et al. [2], meteorite accumulation/preservation in this region is episodic and controlled by climate variations.

Antarctica: Meteorites in Antarctica can be in one of two thermal states: (1) buried in the ice or (2) exposed on the ice surface. When on the surface of the ice, meteorites can have temperatures higher than the air as a result of solar heating [16]. Calculations indicate that the rates of TL decay at temperatures experienced while encased in the ice are insignificant compared to those at surface temperatures. Thus, the natural TL level of an Antarctic meteorite find is largely determined by the "surface exposure age" rather than the total terrestrial age.

We have calculated surface exposure ages for a group of meteorites for which terrestrial ages, largely determined from ^{36}Cl abundances [17], are available (Fig. 4). To make this calculation we assume an average surface exposure temperature of −15°C [16] and an initial TL level of 100 krad [18]. Ignoring the group of meteorites with apparently small terrestrial ages but very large surface exposure ages because these are "reheated meteorites" that are also observed in every other database (i.e., Figs. 1b and 2), there is a large range of exposure ages. Most meteorites spent ≤50% of their terrestrial histories exposed on the ice surface. There appears to be a hiatus in exposure ages between about 0.18 and 0.2 m.y., and a "ceiling" at about 0.25 m.y. with even meteorites with terrestrial ages ≈1 m.y. having surface exposure ages of ≈0.2 m.y. Either 0.2 m.y. is the length of time required to move a meteorite across a blue ice field and back onto active ice or an event cleared the ice field of meteorites with surface exposure ages >0.25 m.y. One could also interpret the meteorites with small surface exposure ages and small terrestrial ages as locally derived, while those with greater surface exposure ages and terrestrial ages could represent meteorites derived from some distance away and transported to the field by the ice. In this case, our data agree with the suggestions of Huss [19] in

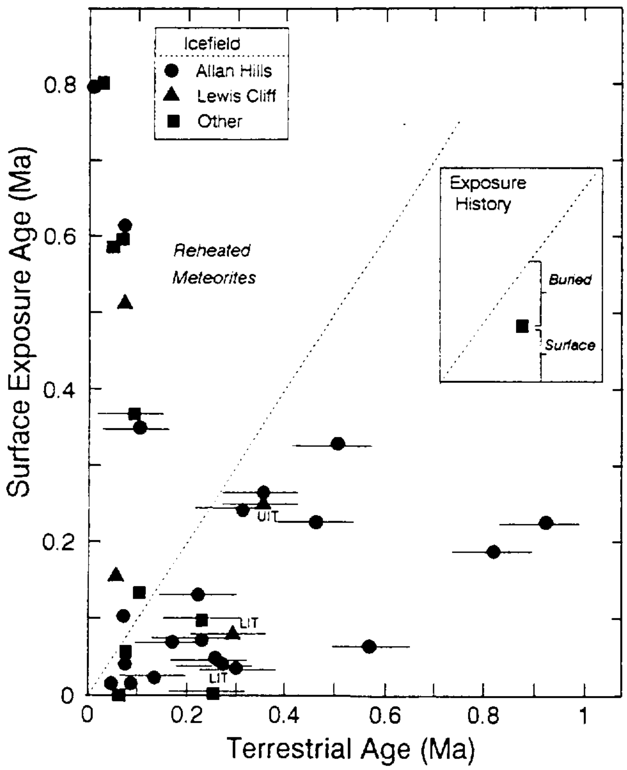

Fig. 4. Antarctic ordinary chondrites.

that it appears that locally derived meteorites dominate the dataset.

The data shown in Fig. 4 are dominated by meteorites from the Allan Hills Main and Near Western Ice Fields. We have previously suggested on the basis of natural TL data that there are differences in surface exposure ages between fields and, in a few cases, in regions within fields. Among our observations, we have noted that there are apparent differences in surface exposure ages between the Elephant Moraine Ice Fields and the Allan Hills Main Ice Field, with the Elephant Moraine meteorites generally having fairly small surface exposure ages [18]. We have also noted that there are differences between the Lower and Upper Ice Tongues at the Lewis Cliff site, with meteorites from the Lower Ice Tongue having apparently lower surface exposure ages than those from the Upper Ice Tongue [20]. The cosmogenic radionuclide database for Lewis Cliff meteorites is still very small, but two meteorites from the Lower Ice Tongue plot with the group with small terrestrial ages and small surface exposure ages, whereas a single Upper Ice Tongue meteorite plots with the meteorites with high surface exposure age.

Conclusions: We have used natural TL data to determine terrestrial ages and, in the case of Antarctic meteorites, surface exposure ages. We find that there is evidence that meteorite accumulation/preservation has been episodic in the western U.S. and the Sahara desert. This presents difficulties in estimating meteorite flux from numbers of meteorites on accumulation surfaces [e.g., 12]. We also find that Antarctic meteorite accumulation surfaces may also be episodic in activity and that some fields are more "stable" than others.

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THE ANTARCTIC COLLECTION AND CHANGES IN THE METEORITE FLUX OVER TIME: THE LINGERING DEATH OF A SUBGROUP OF H CHONDRITES.

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Differences between the Antarctic meteorite find collection and modern falls have been noted since the initial Antarctic expeditions. Among the more obvious differences are the lesser abundance of iron meteorites among Antarctic meteorites compared to modern falls and a tendency for Antarctic meteorite finds to be smaller than their equivalents among non-Antarctic meteorites [1,2]. On a finer scale, differences have been noted in the diversity of types of iron meteorites in the Antarctic collection compared to modern falls [3] and in trace-element concentrations between H5 chondrites in the two collections [4]. The significance of some of these differences is uncertain due to the effects of weathering and the largely unknown amount of "pairing" within the Antarctic collection [2,5]. Differences have not been observed in the cosmic ray exposure (CRE) age distribution for ordinary chondrites [6] and in nonvolatile bulk composition [7]. Here we review the induced thermoluminescence (TL) database for H chondrites, which, together with metallographic cooling rates, does show a difference between the Antarctic and non-Antarctic meteorite collections and, in fact, indicates that the difference correlates with terrestrial age within the Antarctic collection. We present new data on H6 chondrites, discuss ^{26}Al data for H chondrites, and discuss the implications of these data for changes in the meteorite flux over the last few hundred thousand years.

The induced TL data for H5 chondrites from the Allan Hills show two distinct groups, one with TL peak temperatures <190°C and the other with peak temperatures >190°C (Fig. 1) [8,9]. The latter group is significantly different in induced TL properties from H5 chondrites in the modern falls. We have suggested that the difference in TL peak temperatures is the result of different thermal histories; either the meteorites of the >190°C group cooled through the order/disorder transition of feldspar more rapidly than meteorites of the

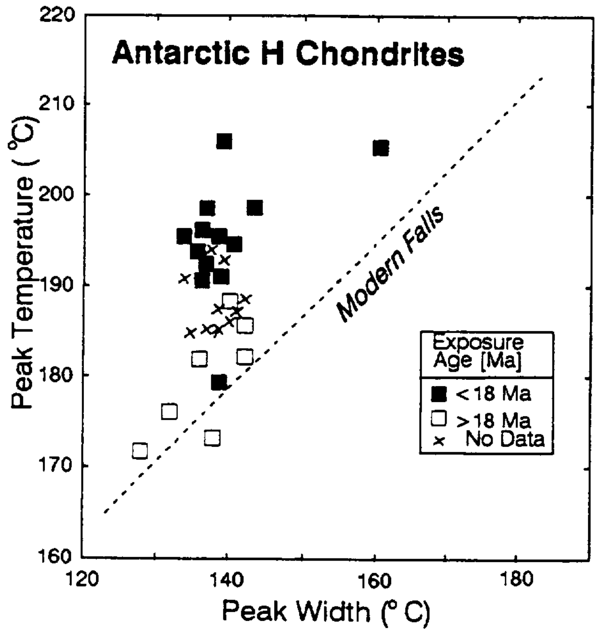

Fig. 1. Antarctic H chondrites.

<190°C group, or these meteorites were annealed at high temperatures subsequent to crystallization. Meteorites of the >190°C group have significantly higher metallographic cooling rates, >100 K/m.y. compared to about 30 K/m.y. for the members of the <190°C group. The >190°C-group meteorites share two other properties, namely, they all have CRE ages of about 8 m.y. (although not all Antarctic meteorites with 8-m.y. exposure ages belong to this group) and they generally have relatively large $^{3}He/^{21}Ne$ and $^{22}Ne/^{21}Ne$ ratios, which is indicative of a fairly small size during irradiation in space. Petrographic observations do not indicate that the meteorites of the >190°C group were shocked to a greater degree than meteorites of the <190°C group [9]. Weathering does not explain the >190°C group because (1) hand-specimen descriptions of meteorites of the >190°C group do not indicate that they are more weathered than those of the <190°C group [9]; (2) laboratory acid washing experiments indicate that, while weathering does reduce the overall induced TL sensitivity of Antarctic meteorites, it does not change TL peak temperatures or widths [10]; (3) the metallographic profiles in these meteorites cannot be modified by weathering; and (4) this behavior is restricted to samples with CRE ages of 8 m.y. and there is no reason that weathering would be selective on the basis of CRE age. Furthermore, this group is not caused by "pairing" of a single unusual meteorite. Natural TL and cosmogenic noble gas data [6,9] are not consistent with the distribution of induced TL being due to pairing. Nor are there large numbers of regolith breccias in this group, as was suggested by Kallemeyn et al. [7] in their study of bulk chemistry. The >190°C group appears to be correlated with the differences observed in trace-element studies of H chondrites [4,11]. We will hereafter refer to the >190°C meteorites as the "rapidly cooled" H chondrites and the <190°C group meteorites as the "normal" H chondrites.

We suggested on the basis of data from the TL survey of Antarctic meteorites [9] that the rapidly cooled group included H chondrites of types 4 and 6 in addition to the petrologic type 5 meteorites that dominated the original study. We described H4 chondrites that belonged to this group, using both induced TL data and metallographic cooling rate data [12]. We have recently been examining a collection of Antarctic H6 chondrites, as well as a group of H6 modern falls for comparison. Thus far we have obtained new induced TL data for 12 Antarctic H6 chondrites; metallographic data will be obtained in the near future. Of the 12 Antarctic meteorites, only three, Mount Baldr 76001, Meteorite Hills 78019, and Allan Hills 80126, appear to belong to the rapidly cooled H chondrite group, and one of these has a CRE age of about 8 m.y. (no CRE age data are available for the other two). As was the case for the H4 and H6 databases, most of the Antarctic H6 chondrites that have normal induced TL peak temperatures have CRE ages greater than 18 m.y. There are two exceptions to this rule, namely Allan Hills 76008, which has an apparent CRE age of about 2 m.y., but has been previously documented to have a multiphase CRE history with a total exposure time of well over 20 m.y. [6] and Allan Hills 81037, which has a CRE age of about 8 m.y. but is apparently a member of the normal H chondrite group. It is thus equivalent to many H chondrites among the modern falls, many of which have CRE ages of about 8 m.y., but all of which have normal induced TL and metallographic cooling rates. The discovery of a meteorite like Allan Hills 81037 in the collection is not unexpected and, in fact, the apparent rarity of such meteorites, as will be discussed below, largely reflects a bias created in most Antarctic-non-Antarctic meteorite comparison studies, which tend to use the Allan Hills collection as a proxy for Antarctic meteorites as a whole.

From our ongoing survey of Antarctic meteorites we have observed that the relative abundance of rapidly cooled H chondrites varies from site to site. We have noted that the rapidly cooled H chondrites are common at the Allan Hills sites and at the Lewis Cliff Upper Ice Tongue, rare at the Yamato Ice Field, and virtually absent at the Lower Ice Tongue and Meteorite Moraine at Lewis Cliff [9] and all ice fields in the Elephant Moraine region [13]. We have previously suggested that this variation in abundance reflects the average terrestrial age of the populations of H chondrites from each ice field, although the exact ranking of the ice fields is somewhat arbitrary because (1) the cosmogenic radionuclide database for most of these fields (at least for ordinary chondrites) is very small or nonexistent, and (2) even where such data are available, they typically provide only upper limits. Nonetheless, it appears that the average terrestrial age for meteorites from the Allan Hills is about 200,000 yr [14], compared to about 50,000 yr for Yamato meteorites and perhaps 20,000 yr at the younger Lewis Cliff sites [14]. Therefore, it appears that the rapidly cooled H chondrite group went from contributing about half the H chondrite meteorite flux to nonrepresentation in the flux over a time span of about 180,000 yr. Lipschutz [4] made a similar observation on the basis of trace-element data for H chondrites from only the Allan Hills and the Yamato sites. It should be noted that we have failed to find rapidly cooled H chondrites at any of the non-Antarctic find concentrations that we have examined thus far (including Roosevelt County, finds from the western U.S., and the Sahara Desert). Most meteorites from these sites have terrestrial ages of <40,000 yr, and most of these sites are dominated by meteorites with terrestrial ages <10,000 yr [16,17].

A better test of the apparent change in the nature of the H chondrite flux over a fairly short time period would be a direct comparison between distributions in terrestrial ages for rapidly cooled H chondrites and normal Antarctic H chondrites, both with

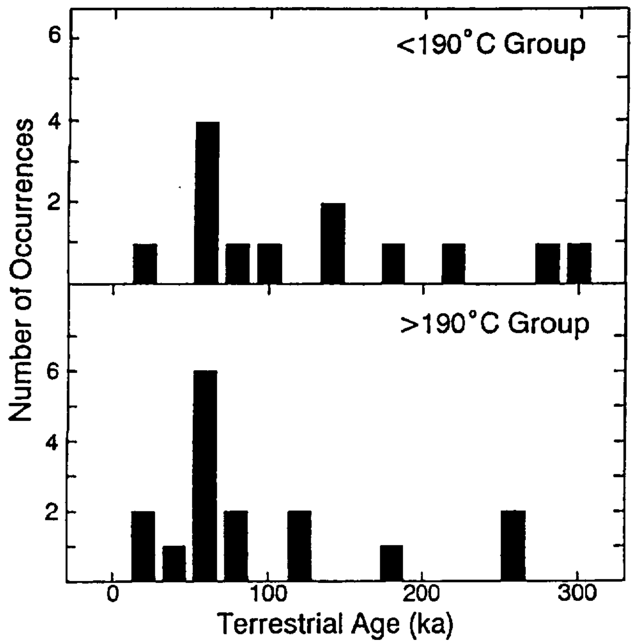

Fig. 2.

8-m.y. exposure ages. Such a comparison is hampered by the small number of Antarctic meteorites for which there is induced TL, metallographic, cosmogenic noble gas, and radionuclide data, all of which would be required for each meteorite in this analysis. Even more crippling to such a study, however, are the limitations of the terrestrial dating techniques, since the age range of most interest, between ~40,000 and 200,000 yr, is just above the upper limit of ^{14}C. It is possible to estimate ages in this range using ^{36}Cl [14], but the uncertainties inherent in these data in this age range are so great as to make any comparison very difficult. Nonetheless, we show a first attempt at such a comparison in Fig. 2, using the ^{36}Cl-dominated databases of Nishiizumi [14] and some recent data of Lipschutz [18]. In this figure we subdivide the meteorites on the basis of induced TL into the normal and rapidly cooled groups and, considering that most of these meteorites are from the Allan Hills collection, we expect that most of the normal H chondrites have CRE ages >18 m.y., while the rapidly cooled meteorites probably all have CRE ages of about 8 m.y. It should be noted that in both distributions the apparent "peak" at about 70 k.y. represents the lower limit of ^{36}Cl-derived terrestrial age estimates and that the meteorites in this peak may actually be spread among lower terrestrial ages. The data are too sparse for any statistical treatment, but it appears that most rapidly cooled meteorites have terrestrial ages <100 k.y. and, in contrast to normal H chondrites, very few have terrestrial ages >120 k.y.

Our present ideas about the changes in the H-chondrite flux over the last few hundred thousand years are summarized in Fig. 3. Meteoroid bodies of normal H chondrites have been part of the meteoroid flux for a considerable period of time, as evidenced by their long CRE ages (>18 m.y.). At about 8 m.y., many meteoroid bodies of both normal and rapidly cooled types were produced. We have suggested that the meteoroids of the rapidly cooled H chondrites evolved to Earth-crossing orbits faster than the normal H chondrites from the same event due to their smaller size, but it could also be argued that this difference reflects asteroid source region

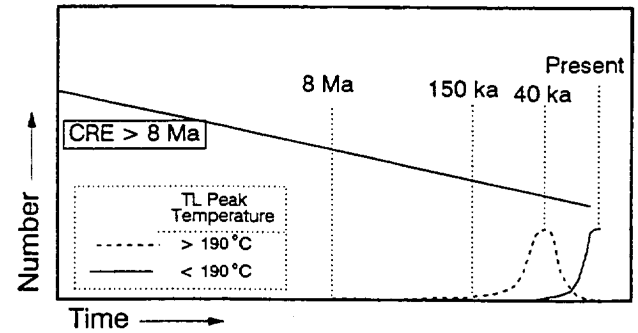

Fig. 3. H chondrites terrestrial flux.

differences [3]. In any case, as is apparent from the terrestrial age data (Fig. 2), at about 50,000–100,000 yr ago the H-chondrite flux was dominated by rapidly cooled H chondrites. Shortly after 40,000 yr ago, however, their abundance in the meteorite flux dropped considerably and normal H chondrites, including those from the 8-m.y. event, dominated the flux. By about 20,000 yr ago the rapidly cooled H chondrites had ceased to make any contribution to the meteorite flux and this has continued up to the present time. In order to examine the orbital history of the H-chondrite groups in more detail, we have also examined their ^{26}Al and natural TL distributions; we discuss only the ^{26}Al data here. Using data from Evans and Reeves [19] and the Antarctic meteorite database [20], and classifying meteorites to normal and rapidly cooled groups using only induced TL, we find the distributions shown in Fig. 4. It is apparent that the normal H chondrites have a ^{26}Al activity distribution similar to the

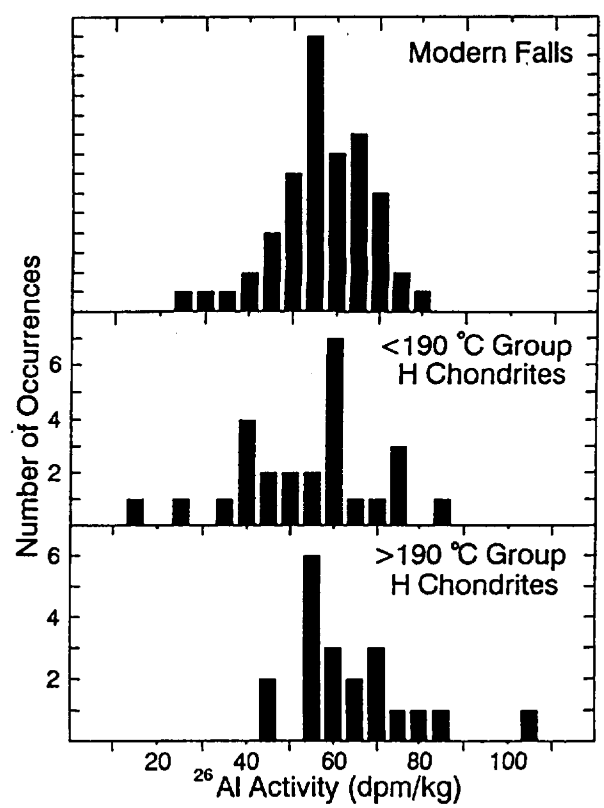

Fig. 4.

modern falls, with perhaps a slight excess in meteorites with low ^{26}Al activities, which would be expected in a group of meteorites that exhibit a broad range of terrestrial ages (Fig. 2). The rapidly cooled H chondrites, however, have a distribution that is significantly different from either normal Antarctic H chondrites or modern falls, with all rapidly cooled H chondrites having high ^{26}Al activities. This is in agreement with the generally small terrestrial age of these meteorites (Fig. 2), but the activities of many of the meteorites are higher than even the modern falls. These differences may reflect the smaller size during irradiation of the rapidly cooled Antarctic meteorites [9], but could also reflect different external radiation fluxes for these meteorite populations, perhaps as a result of high inclination orbits.

In closing, we would note that there are many facets of the Antarctic H chondrites that could and should be explored in more detail. More terrestrial age data would be extremely useful, although their utility is, as noted above, somewhat limited by the lack of accurate dating techniques in the age range of interest. Perhaps more interesting would be an attempt to document the rise in abundance of the normal H chondrites from the 8-m.y. event (such as Allan Hills 81037) over the last few tens of thousands of years. Only the modern falls in this group have been studied in any detail, and this group is generally not found in Antarctic studies due to the tendency for these studies to concentrate on meteorites from the Allan Hills. We would suggest that H chondrites from Elephant Moraine, Yamato, and selected portions of the Lewis Cliff site would be ideal for this study.

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IRON-57 MÖSSBAUER SPECTROSCOPY STUDIES OF WEATHERING IN ORDINARY CHONDRITES FROM ROOSEVELT COUNTY, NEW MEXICO.

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Introduction: Meteorite weathering can be regarded as the alteration of original component phases of the meteorite to phases that are more stable at the Earth's surface. On entering the Earth's atmosphere, interaction with the terrestrial environment begins. Meteorites are uniquely placed among geological materials in that they show relatively minor intragroup variations and their terrestrial age can be established by measuring the decay of cosmogenic radionuclides by accelerator mass spectrometry [1]. They are therefore a potential "chronometer" of environmental conditions during their terrestrial residency. Being the most common meteorite type and having a tightly constrained mineralogy [2], ordinary chondrites are ideal candidates for investigating terrestrial weathering products in meteorites. Their relatively high Fe content makes them suitable for examination by ^{57}Fe Mössbauer spectroscopy.

Arid climate, uniform topography, and lack of a concentration/movement mechanism makes it likely that meteorites throughout Roosevelt County were weathered by a common mechanism. Jull et al. [3] showed a correlation in meteorites from Roosevelt County between terrestrial ^{14}C ages and a qualitative weathering scale. We report here on our examination of a suite of meteorites by ^{57}Fe Mössbauer spectroscopy recovered from Roosevelt County, for which terrestrial ages have been determined [3]. Fresh fall meteorites, Allegan (H5) and Barwell (L6), were used as unweathered standards for the purposes of this study.

Meteorite Specimens: Meteorites were obtained from the Natural History Museum, London, and the Max-Planck-Institut für Chemie, Mainz, Germany. Approximately 0.5–1.0 g of sample was used, prepared by grinding under acetone to prevent oxidation during crushing, until a homogenized powder was produced. Mössbauer spectra were recorded at 298°K and 77°K with a microprocessor-controlled Mössbauer spectrometer using a $^{57}Co/Rh$ source. Drive velocity was calibrated with the same source and a metallic Fe foil. The Mössbauer spectra were fitted with a constrained nonlinear least-squares fitting program of Lorentzian functions. The fitted lines were integrated to give the relative area intensities of the Fe-containing phases in the sample.

Results and Discussion: *Components of Mössbauer spectra.* The Mössbauer spectra recorded from Barwell and Allegan validate the assumption that these samples represent unweathered meteorites: No Fe^{3+} was detected in either of these samples. However, spectral components associated with Fe-Ni metal, troilite, olivine, and pyroxene [4] were recognized. The Mössbauer spectra recorded from Roosevelt County meteorites showed similar features but with different intensities of the separate components. In addition, absorptions associated with Fe^{3+}-containing terrestrial corrosion products were observed, with a concomitant reduction in the spectral area of preterrestrial meteoritic minerals.

Although the Mössbauer parameters of Fe oxides and oxyhydroxides are similar, they are sufficiently different, particularly when spectra recorded at 298°K and 77°K are compared, to allow the assignment of individual phases. In this study, spectra recorded at room temperature and at liquid N temperatures indicate the presence of goethite, magnetite, maghemite, and akaganéite. Ferrihydrite and lepidocrocite are also tentatively identified. This suite of oxidation products corresponds to that observed by [5] and [6] in an electron microprobe, SEM, and XRD study of weathered meteorites. This would suggest a broadly similar corrosion mechanism to that proposed by [5], with akaganéite precipitating at the reaction front as metal goes into solution, and with time and distance

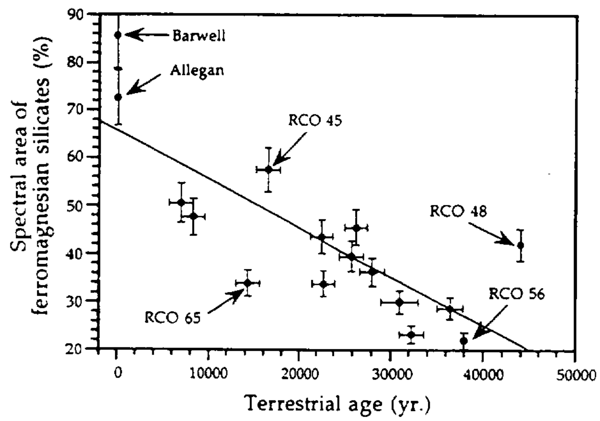

Fig. 1. The spectral area of ferromagnesian silicates against terrestrial residence time in Roosevelt County ordinary chondrites Barwell and Allegan.

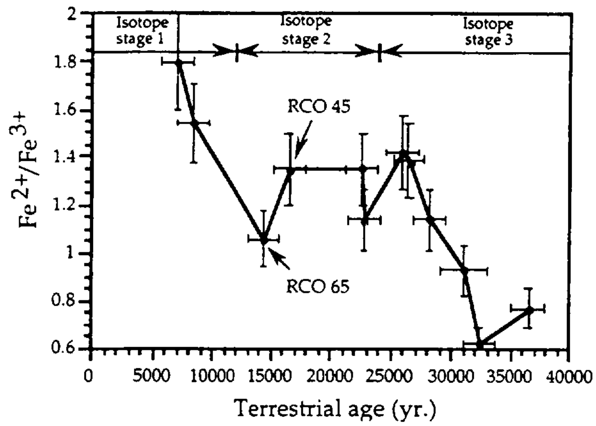

Fig. 2. Ratio of Fe^{2+}/Fe^{3+} against terrestrial residence time in ordinary chondrites from Roosevelt County.

from the reaction surface, gradually transforming to maghemite and goethite. Magnetite has been observed as a significant corrosion product in hot desert meteorites by [6], and it is also a common component in the Mössbauer spectra from the Roosevelt County meteorites described in this study. In a similar study of a suite of Antarctic H chondrites, we found no absorption associated with magnetite in the Mössbauer spectra from these samples. A possible explanation for this may be that in the relatively warmer and more humid environment of a hot desert, the rapid dissolution and oxidation of Fe-Ni (containing Fe^0) may produce a solution around Fe-Ni grains that is saturated with Fe^{2+}, before these ions are also oxidized to Fe^{3+}. Although the relatively minor proportion of Fe-Ni remaining in Roosevelt County meteorites does not allow such a saturation effect to be observed, it is possible that the presence of these two Fe species allows the stability of magnetite, which may then persist in this environment as a metastable reaction product [7]. The oxidation of olivine and pyroxene may give rise to Fe oxyhydroxides such as ferrihydrite, lepidocrocite, and goethite [8].

Relationship between weathering and terrestrial age. The contribution to the Mössbauer spectra from the ferromagnesian silicates olivine and pyroxene has been calculated from computer-fitted spectra recorded from Barwell and Allegan, and a suite of Roosevelt County meteorites. The data are plotted against terrestrial age in Fig. 1. A clear trend is observed showing a decreasing contribution from these phases with increasing terrestrial age. The linear fit to this data is significant at better than the 99% level, indicating a rate of dissolution and oxidation for ferromagnesian silicates of approximately 5% per 5000 yr. This would imply the complete oxidation of these silicates to secondary Fe oxides and oxyhydroxides in Roosevelt County ordinary chondrites after around 60,000 yr, thus giving an approximate upper limit to the residence time of meteorites such as Roosevelt County 48 and Roosevelt County 56 for which ^{14}C dating can only provide a minimum terrestrial age [3].

Interestingly, two of the meteorites that deviate most from this line (Roosevelt County 45 and Roosevelt County 65) fell at a time when climatic conditions in Roosevelt County and much of the rest of North America were changing dramatically [9,10], at the end of the last glaciation. A plot of Fe^{2+}/Fe^{3+} [derived by combining the spectral areas of Fe^{2+}-containing phases (olivine, pyroxene, and troilite) and dividing by the combined spectral areas of Fe^{3+}-containing phases] against terrestrial age also indicates the possibility of a climatic control on meteorite weathering. The period of the Quaternary over which these meteorites fell has been divided by [11] into three stages, using an O isotope stratigraphy; these stages are shown on Fig. 2. It is clear from this diagram that there is some correlation between meteorite weathering over time and the independently measured O isotope stratigraphy, that is itself a function of climatic changes during the late Quaternary. Figure 2 shows a regular increase of Fe^{2+}/Fe^{3+} between 32,300 and 25,900 BP (isotope stage 3), followed by a period of relatively little oxidation, then a drop to lower Fe^{2+}/Fe^{3+} values around 14,000 BP (isotope stage 2) before a steady increase again (isotope stage 1). The meteorite falls in Roosevelt County span a period up to, or exceeding, 50,000 yr [3]. As such, the oldest meteorites from this region fell to Earth during the middle of the last glaciation. The period following this time (up to ~24,000 BP), characterized by [11] as isotope stage 3 (this corresponds approximately to the Middle Wisconsin stage in the U.S. and Canada), involved fairly stable climatic conditions. This period is widely recognized as an episode of general climatic amelioration in North America, involving retreat and decay of the Laurentide and Cordillerian ice sheets [12]. In fact, it has been suggested by [13] and [14] that these ice sheets may have melted completely during the Middle Wisconsin. Although there is little local evidence of what the climate was like in Roosevelt County at this time, the overall picture of climatic amelioration in North America may have produced an environment not dissimilar to that which we observe today, leading to a similar rate of weathering in meteorites that fell during this time to those that fell during the last few thousand years. The culmination of the last glacial maximum occurred at 18,000 BP [15]. This period saw the lowest temperatures at any time during the 110,000 yr of the last glaciation [16]. It is possible that this depressed the rate of chemical weathering reactions, causing relatively little oxidation in the meteorites that fell around this time. Between the time when Roosevelt County 45 and Roosevelt County 65 fell, temperatures increased rapidly worldwide [16], leading to melting of glaciers, increased runoff, and increased precipitation. Meteorites falling after this period, during which climate was relatively stable, would show more gradual oxidation.

Postulating a climatic control for this difference in weathering rate requires that meteorites with older terrestrial ages were protected in some way during the period of increased chemical weathering, i.e., samples must "remember" a previous milder weathering regime, rather than lose the information during periods of increased weathering. Schott and Berner [17] found that oxygenated dissolution of Fe-rich minerals (in this case olivine) leads to the formation of two surface layers, the inner layer being an Fe^{3+}-Mg silicate that could be protective toward further dissolution. More recently, [18] have observed laihunite (an Fe^{2+}, Fe^{3+}, Mg silicate) as an alteration product of olivine, forming intergrowths with the original crystal that increase its resistance to weathering. The role of surface species in controlling the low-temperature dissolution of minerals has also been emphasized by [19]. If protective stable oxide layers do have a passivating role in the continued oxidation of primary meteorite phases, meteorites may survive periods of more intense weathering, in effect preserving an assemblage of primary and secondary minerals that was produced during a different climatic regime. Such oxides may act to protect meteorites with longer terrestrial ages during times of increased weathering, while meteorites falling during such periods, i.e., starting their weathering history, may experience higher rates of oxidation.

Conclusions: This study has shown that ^{57}Fe Mössbauer spectroscopy is a promising means by which the course of oxidation and the nature of the weathering processes in meteorites may be identified. The weathering of ordinary chondrites in Roosevelt County is seen to be a function of time and of climatic changes that have occurred during the meteorites' terrestrial residency. We have also conducted a similar study of Antarctic H chondrites, and these meteorites do not show this effect. It seems likely that, as suggested by [20], time exposed on the ice surface rather than absolute terrestrial age may be the controlling factor in weathering of Antarctic meteorites.

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PYROXENE, THE INDICATOR OF PERVASIVE TRACE-ELEMENT MOBILIZATION IN ANTARCTIC METEORITES. G. Crozaz, Department of Earth and Planetary Sciences and McDonnell Center for the Space Sciences, Washington University, St. Louis MO 63130, USA.

The discovery of large numbers of meteorites in Antarctica has stimulated many cosmochemical studies; new meteorite types were recognized and groups of rare meteorites were greatly expanded. In addition, the availability of meteorites that fell much earlier (tens to hundreds of thousands of years ago) than those represented in the museum collections provided the opportunity to compare these two populations of objects. Of critical importance to these comparisons has been the question of whether compositional differences between meteorites of a given group were generated in their parent body or bodies or whether they reflect the extremely different terrestrial histories experienced by Antarctic and non-Antarctic meteorites.

It was first assumed that Antarctic meteorites had remained essentially unchanged in their cold and dry environment, but we then realized that weathering, although at a slow rate, had been at work. The presence and abundance of rust became and still is the basis for the weathering classification of these objects; they guided the choice of meteorites to be studied by cosmochemists. However, the production of rust depends not only on the length and intensity of weathering, but, more importantly, on the amount of Fe-Ni metal and troilite present in the sample. Some meteorites (e.g., eucrites, SNCs, etc.) are metal and sulfide poor and thus, even after severe weathering, may not be recognized as altered.

In eucrites, there is considerable evidence that the REEs, so widely used in petrogenetic modeling, were disturbed [e.g., 1]. Mittlefehldt and Lindstrom [1] have shown that many of the Antarctic eucrites they analyzed (~60%) have REE patterns with positive (and sometimes negative) Ce anomalies, positive Eu anomalies, and low abundances of the remaining REEs. Their data strongly imply that while in or, most likely, on the ice, eucrites are altered and lose part of their REEs. These authors attributed the Ce anomalies to the partial oxidation Ce^{3+} to Ce^{4+} and the partitioning of the more insoluble Ce^{4+} from the other REEs when dissolution of the major REE carriers in eucrites, the calcium phosphates, occurred. Dissolution of these minerals was promoted by the production of an acid solution while the meteorite was residing on the ice surface. Because the phosphates are located in interstitial material, it was assumed [1] that the major silicate phases were left intact and thus are suitable for petrogenetic modeling. Ion microprobe measurements of REE concentrations in individual grains, made in our laboratory and described below, confirm the importance of phosphate dissolution in altering the whole-rock patterns but also demonstrate that other types of meteorites, as well as minerals other than phosphates, most prominently and commonly pyroxene, were significantly affected by weathering processes.

That the weathering of phosphate tends to leach the REEs leaving Ce preferentially behind was accidentally supported by observations in an acid-etched section of the heavily shocked shergottite Allan Hills 77005. The REE patterns of individual merrillite grains (Fig. 1) are identical except for positive Ce anomalies whose sizes correlate positively with the apparent REE concentrations. A range of REE concentrations is observed (factor of 25) that clearly exceeds the variation expected during closed-system crystallization of a melt. In fact, the range of concentrations is not real but an artifact of the Ca normalization used to derive the data. The results imply that Ca and the REEs were all leached but that Ca and Ce were, respectively, the easiest and the most difficult elements to mobilize. In contrast, analysis of an unetched section of the

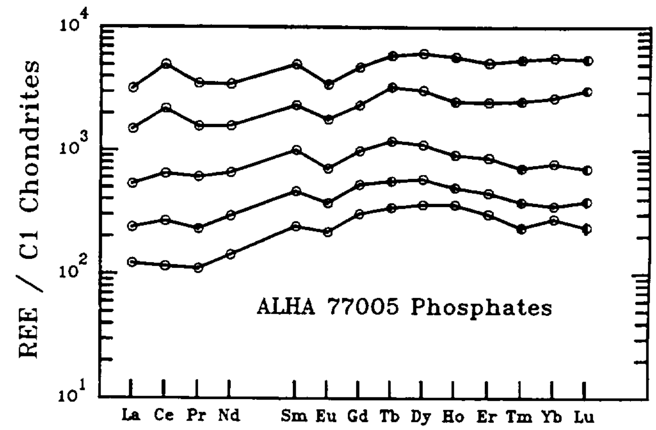

Fig. 1. Apparent REE abundances in five merrillite grains from ALH 77005.

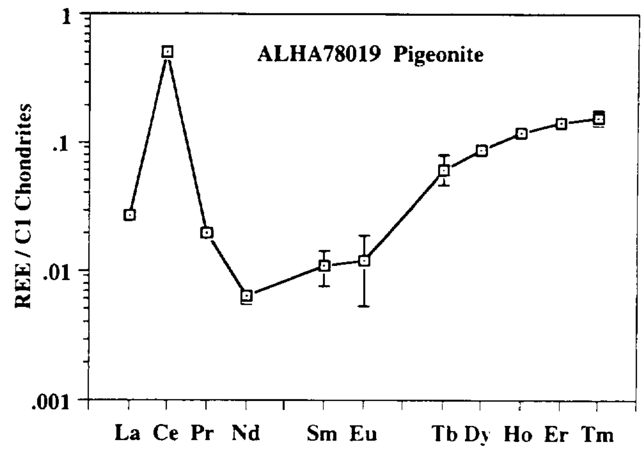

Fig. 3. REE pattern with a striking positive Ce anomaly in pigeonite from the ureilite Allan Hills 78019.

same meteorite did not reveal any Ce anomalous merrillite [2]. In eucrites, there are three factors that facilitate REE leaching from Ca phosphates: Grains of these minerals (1) are typically smaller than in other types of objects, (2) are unusually rich in actinides (which caused extensive radiation damage), and (3) in meteorites that have undergone a significant shock event, have acquired numerous shock-induced defects.

Leaching of REEs from phosphates not only produces a net loss of these elements but also leads to their redistribution within the meteorite itself. Other minerals, particularly pyroxene, are also affected. In a detailed study of a eucrite [3], we showed that plagioclase, pyroxene, and silica can all have Ce anomalies (positive and/or negative). Pyroxene was most affected (38 out of 52 grains had Ce anomalies) because it has an extensive, shock-induced network of microcracks.

Conversely, Ce anomalies are rare in plagioclase (in only 2 out of 17 grains) because it lacks a network of defects along which REEs can be mobilized. No single explanation can account for the observations in pyroxene. Whereas the negative Ce anomalies (present in 12% of the analyses) could be due to the addition of REEs (minus Ce) generated by the phosphate dissolution, the positive Ce anomalies (in ~60% of the analyses) suggest that the REE redistribution mechanism is actually much more complex and involves leaching from the pyroxene itself. In this context, it should be noted that the distribution of Ce anomalies in pyroxene is quite heterogeneous, even on a scale of just a few hundred micrometers. A series of eight analyses along a single pyroxene grain resulted in REE patterns that have positive, negative, or no Ce anomalies, with no obvious trend according to location.

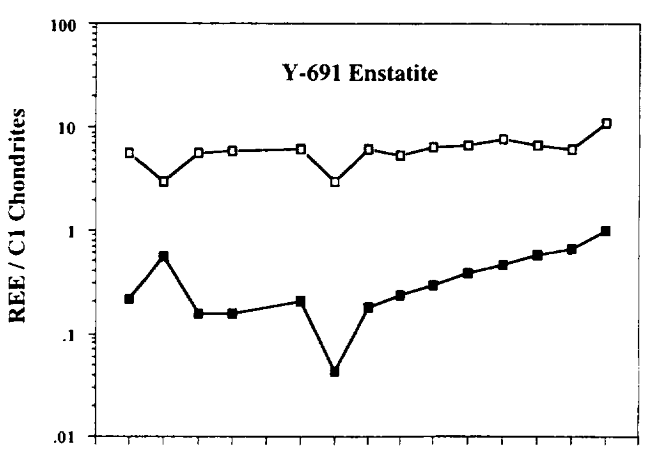

Fig. 2. REE patterns with Ce anomalies in enstatite grains from the EH3 chondrite Yamato 691.

Since the analysis of this eucrite (whose whole-rock REE pattern has a Ce anomaly), more anomalies have been found in pyroxene from meteorites in which the weathering effects are less obvious (i.e., do not result in a bulk REE pattern with significant Ce depletion or enrichment). These observations are a by-product of our ongoing petrogenetic studies that rely on the use of the ion microprobe. Without any exception, all the meteorites that contain pyroxene with Ce anomalies were found in Antarctica. To date, they include all the Antarctic shergottites, Allan Hills 77005, Elephant Moraine 79001, and Lewis Cliff 88516, which are heavily shocked, and the EH3 chondrite Yamato 691. Cerium anomalies in Yamato 691 enstatite (Fig. 2) are rare (only two examples out of tens of grains) and are presumably due to the oxidation and dissolution of oldhamite (CaS), the major REE carrier in enstatite meteorites. We also found (Fig. 3) a pigeonite in a ureilite from Antarctica with a very pronounced positive Ce anomaly. Thus, it is clear that REE mobilization was not limited to eucrites, but affected to various degrees many different types of meteorites.

In conclusion, weathering in Antarctica not only results in REE loss but also extensive redistribution within the meteorites. Pyroxene, particularly when shocked, is a sensitive indicator of these processes. Therefore, it is risky to assume that the major silicate phases of Antarctic meteorites remained pristine and that they can always be used in petrogenetic modeling.

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STORAGE OF METEORITES IN ANTARCTIC ICE DURING GLACIAL AND INTERGLACIAL STAGES. G. Delisle, Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Postfach 51 01 53, D-30631 Hannover, Germany.

Introduction: Antarctic meteorites are better preserved over longer time periods than material from hot deserts. Ice is clearly an ideal host material for storage. Nevertheless, there is evidence that many meteorites periodically reach the blue ice surface, where they moisten, refreeze, and experience similar weathering and decay processes to their counterparts in hot deserts before they are reburied and isolated in deeper ice levels.

The purpose of this paper is to discuss two points: (1) The field situation in which Antarctic meteorites are found today is most likely not typical of their long-term storage mode; (2) there is field evidence for movement of fluids and/or gaseous components in surficial ice during the Antarctic summer season.

Antarctic Meteorite Traps: The major Antarctic meteorite concentrations are found at elevations between 1900 and 2400 m above sea level. Computer simulations on the response of the East Antarctic ice sheet to glacial stages (climatic deterioration) predict for this "meteorite trap terrain" a higher ice stand and shallower surface slope than today [1–3]. The reasons are as follows: The decrease in precipitation during a glacial stage (cooler and dryer air) over central Antarctica in combination with the cooling of the ice cap causes a thinning of the central East Antarctic ice sheet and thickening along the coastal regions. However, during an interglacial stage, the process reverses (coastal ice shrinks, the central ice sheet thickens). A computer model by [3] postulates that the area of zero ice stand fluctuation is located near the 2700-m elevation line. The known meteorite traps are all located on the coastal side of this "hinge line." They should experience ice thinning (e.g., 100–300 m according to [3]) during an interglacial stage and a return to thicker ice during glacials. The duration of "glacial stages" is on the order of 110 b.y., while interglacial stages (as we currently live in) last for roughly 15 b.y.

What are the consequences during glacial stages? The shallower surface slope and the cooling of the ice tend to reduce ice velocities and mass transport. An increase in ice thickness in combination with an unchanging ice ablation rate (here assumed for the sake of the argument) tend to speed up ice movement. What is the net effect?

Allan Hills: The on-average 200-m-thick, westward-sloping blue ice along the western flank of the Allan Hills is actively decaying today [3]. The once-thicker blue ice was either previously transported to the site from the Antarctic interior or was produced locally during a period of a much higher ice stand sufficient to exert the required overburden pressure to form this dense type of ice. The latter scenario is less likely. A growing snow and ice cover would readily have moved across the shallow Allan Hills toward the coast, for which we have no field evidence (no lateral moraines evident in the field). The above scenarios preclude the concurrent existence of the ice depression east of the Allan Hills Main Ice Field escarpment.

A simplified computer simulation of the ice flow demonstrates that the ice ablation rate during glacial stages must have been much lower than today or even absent, which is the equivalent of saying that a large portion of the current blue ice fields were then covered by firn and snow. Consider a 500-m-high and 8-km-long vertical segment of blue ice. The ice thickness on the left boundary is kept constant (representing the fast-moving ice stream between the Main and Near Western Ice Field [4,5], not subject to ice sublimation). The upper surface of the ice is exposed to ice sublimation at a rate

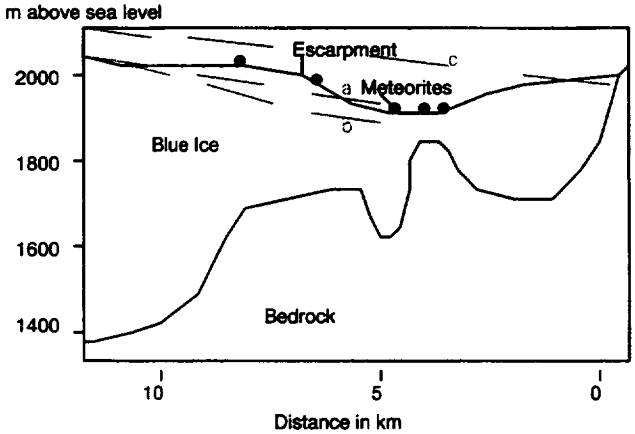

Fig. 1. The approximate outline of the surface and sub-ice topography along a line from the Allan Hills westward and the theoretical ice surface slope for (1) line a: an ice temperature of $-30°$ and an average sublimation rate of 4 cm/yr, (2) line b: an ice temperature of $-40°$ and an average sublimation rate of 4 cm/yr; and (3) line c: an ice temperature of $-40°$ and an average sublimation rate of 2 cm/yr.

of 4 cm/yr for $t > 0$. Eventually, a balance will develop between the ice loss by sublimation and the advected ice. The computer simulation creates an ice surface slope (which is the force driving the advection of ice) of 130 m over a distance of 8 km, which is almost exactly the situation observed in the field today (line a in Fig. 1). If we lower the assumed ice temperature in the model by 10°, the surface slope increases to 190 m over the same distance (line b). The reason is that cooler ice is stiffer and needs a greater surface slope (greater driving force) to maintain the amount of advected ice necessary to balance the ice loss by sublimation. None of these models would account for the presence of blue ice along the western flank of the Allan Hills.

In the past, the local ice sublimation rate must then have been much lower or the regional ice level higher or both. This scenario was tested by the model, now assuming a 600-m-high vertical segment with a length of 12 km, equivalent to the distance between the Allan Hills and the ice stream. The ice sublimation rate was reduced to 2 cm/yr. The calculated surface slope intersects the western flank of the Allan Hills about 50 m below the hilltops (line c in Fig. 1).

It should be remembered that the model assumes constant ice thickness. The rising bedrock near the Allan Hills would in reality steepen the surface slope even further above it. The sublimation rate would have to be lowered further, if the existing bedrock topography were incorporated.

From this consideration it is concluded that field observations strongly suggest, in connection with the above-outlined computer simulation on the ice flow under climatic conditions of the last glacial stage, a higher ice level and a much reduced sublimation rate in the past.

Frontier Mountain: As discussed previously (see Fig. 20 in [6]), the current surface topography at Frontier Mountain most likely evolved through various stages starting from a situation with a regionally higher ice stand and a much reduced surface ablation rate.

Consequence: The postulated processes reduce the exposure rate of meteorites during glacial stages to a minimum. Meteorite occurrences would then be covered by a substantial layer of firn and ice. This scenario pictures the meteorite traps as having operated essentially only during interglacial periods (as today).

Storage Environment in Ice Today: Several boreholes were drilled into ice during the German GANOVEX-VII expedition to Victoria Land (1992–1993). The drilling device (a detailed description can be found in [7]) was an electrically heated sonde that melted its way through the ice. The meltwater was removed from the hole by a bailer. One borehole was drilled into blue ice at a location (75°54,182S, 158°32,778E) due north of Ambalada Peak. No meteorite had ever been found on this blue ice. The site nevertheless offers the typical conditions of Antarctic blue ice fields.

The monitoring of the drilling operation showed that the recoverable amount of meltwater from the borehole varied. The theoretically predicted amount of 5.7 l/m of borehole was recovered down to a depth of −4 m, implying an impermeable ice wall. A sharp reduction down to <1 l/m occurred below that depth down to −10 m.

These observations are interpreted as follows: The blue ice had developed under tension numerous open fissures, which are not obvious at the ice surface. During the summer season any developing fissure is resealed rapidly (water vapor or meltwater?). This process is apparently active down to a depth of about −4 m. Alternatively, thermal expansion of surficial ice, in response to the advancing thermal summer wave, closes open cracks. Fissures below this level are not affected and remain open. The permeability of the ice below this level is apparently sufficient to drain about 30 l of water within half a day from a borehole with a diameter of 8 cm.

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REPORT OF ACTIVITIES UNDERTAKEN BY THE EUROMET/PNRA METEORITE COLLECTION EXPEDITION TO FRONTIER MOUNTAIN, NORTH VICTORIA LAND, DURING THE 1993–1994 ANTARCTIC FIELD SEASON.

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Introduction: This is a report on activities undertaken by the 1993–1994 EUROMET/PNRA meteorite collection expedition to Frontier Mountain, North Victoria Land, Antarctica, an area already recognized as a meteorite trap on the basis of previous finds by the 1984–1985 GANOVEX IV and 1990–1991 EUROMET/PNRA field campaigns [1,2].

The project, carried out within the framework of the IX Antarctic Campaign of the Italian Programma Nazionale delle Ricerche in Antartide (PNRA), foresaw two main objectives: (1) to complete the collection of meteorites in the known productive sites and extend the systematic search into unexplored areas, and (2) to initiate a thorough study of the meteorite concentration mechanism.

A field team of five (L. Folco, I. A. Franchi, A. M. Fioretti, M. Meneghel, and L. Boi) took part in this expedition, operating from a camp downstream of Frontier Mountain, ~3.5 km northeast of the outcrop (72°57'20"S, 160°29'04"E), along the northern edge of the blue ice field (Fig. 1), from December 22, 1994, until January 9, 1994.

Systematic Search for Meteorites—Activities and Results: A systematic search for meteorites was undertaken, both on foot and with skidoos, covering the entire blue ice field and all the local moraines, with the ultimate aim of studying the distribution of finds. Despite bad weather conditions and a widespread snow cover (the blue ice field was initially covered by a continuous bed of snow, which was reduced to about 50% after 10 days by strong winds), the search yielded a further 59 meteorite samples, weighing a total of about 4.5 kg. Meteorites were mainly found in the two previously discovered concentration sites [1,2]. The first, a trap for meteorites of suspected eolian origin, is located ~3.5 km due east of Frontier Mountain on the upwind slope of a morphological depression in the ice, locally trending east-west (Fig. 1). The second is the ice-cored moraine of a valley (unofficially called "Meteorite Valley") in the southern sector of Frontier Mountain. Noteworthy is the recovery of

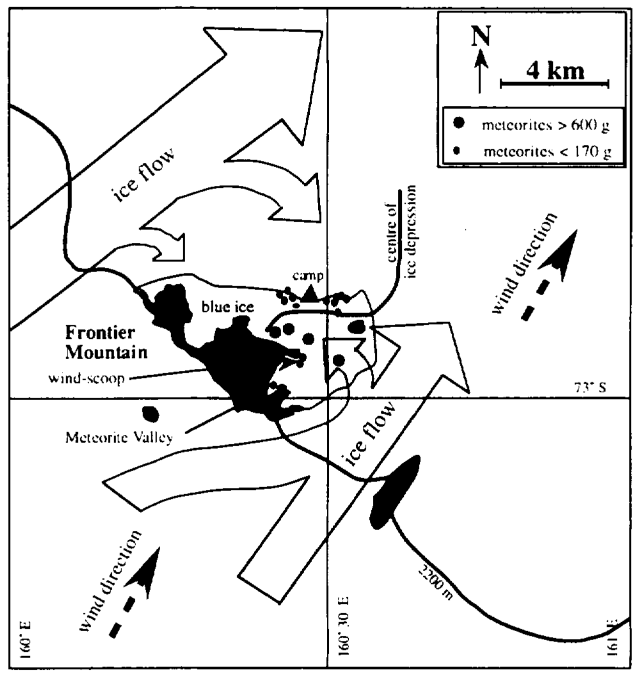

Fig. 1. Schematic map of Frontier Mountain (modified from [5]). The four meteorite concentration sites discovered so far are shown (Meteorite Valley, the wind scoop, the accumulation site of large meteorites, and the eolian concentration area on the upwind slope of the ice depression). The general scheme for meteorite concentration at Frontier Mountain suggested in previous work [1–5] is also depicted by ice flow and wind directions. The ice on the plateau reaches Frontier Mountain from the southwest and passes around it to proceed northeast and ultimately feed the Rennick glacier. As the ice flows past Frontier Mountain, some flows back toward the downstream side of the outcrop. An area of stagnant ice is formed and undergoes high ablation rates caused by katabatic winds blowing from the southwest. The concentration sites on the northern flank of the ice depression and in the Meteorite Valley found during previous expeditions are explained as follows: The meteorite concentration site on the upwind slope of the blue ice depression is of probable eolian origin. Given that the dominant winds at Frontier Mountain blow from the southwest, these meteorites would have been exposed on the erosion surface of the blue ice, in an area yet to be determined, but certainly between the accumulation zone and the eastern foot of Frontier Mountain, and then wind-blown across the blue ice field to reach the firn boundary. Meteorite Valley is an area of intense ablation of stagnant ice. The stagnation is probably due to the collision of an ice flow coming from the plateau and entering the valley's mouth from the east against a volume of ice fed today by a local glacier.

three large samples from 658 g up to 1670 g. These finds, along with a sample weighing 942.3 g found in the 1984–1985 field season [2], identify the strip of blue ice near the southern portion of Frontier Mountain as an accumulation site for particularly large masses. An additional five specimens were recovered in a wind scoop at the foot of the rock cliff, on the northern flank of the Meteorite Valley, where only two samples had previously been found. Thus, the wind scoop may be another accumulation site at Frontier Mountain. No samples were found elsewhere on the blue ice and moraines. However, because of the snow cover, it cannot be stated with certainty that these are unproductive areas.

At the time of this writing, the samples are held at the Open University, the EUROMET center for the curation, classification, and distribution of meteorites to the scientific community. Hand-specimen observations indicate that two or three samples might be of particular interest, possibly including one lodranite of 4.84 g. On the other hand, a couple of specimens look doubtful. All the samples, apart from four specimens that remain deep-frozen because they bear evaporites on their external surfaces, have been dried and weighed. A comparison of the mass distribution of Frontier Mountain samples against all Antarctic meteorites (Fig. 2) mainly shows a deficiency of medium to large samples, namely >32 g, and a higher proportion of small specimens (4–16 g) within the Frontier Mountain population. However, most of the Frontier Mountain samples are almost completely crusted, and therefore it is difficult to appeal to mechanical fragmentation on Earth to account for such a distribution. Hence, the statistics suggest that some meteorites of masses ranging from ~32 g up to 500 g are still missing at Frontier Mountain.

Study of the Meteorite Concentration Mechanisms Active at Frontier Mountain—Activities and Preliminary Results: Much of the field work was devoted to initiating a detailed study of the Frontier Mountain meteorite trap to improve the present understanding of the concentration mechanism [1–5], including attempts to focus on the study of the ice flow dynamics and surface eolian mass transport.

A strain-net-network was installed in order to measure both horizontal ice flow and ablation rates. The grid was placed in the blue ice field, covering areas of interest that were selected on the basis of both field evidence and a study of ice flows through the processing of LANDSAT TM images by M. Frezzotti (ENEA, Roma). Unfortunately, due to unfavorable weather conditions, only 10 out of 18 stakes were positioned by means of the static GPS measurements.

Wind directions were measured by observing wind-carved features (sastrugi and snow drifts), and wind intensity was measured by using a portable anemometer. Throughout the expedition the wind strength constantly exceeded 25–30 knots from south-southwest to southwest. This direction is in agreement with data obtained from satellite images that confirm their prevailing character.

Two "rock races" were set up in the blue ice area in order to evaluate the annual eolian transport in relation to different rock masses and surface morphology. These "rock races" were positioned in areas that might yield information on the possible source regions of the localized accumulation sites of suspected eolian origin located on the northern flank of the ice depression. Here meteorites (typically less than 170 g) were found mixed with millions of local stones arranged in banks perpendicular to the wind direction and parallel to the blue ice-firn boundary. A study was made on mass distribution of these stones, and data (Fig. 3) mainly

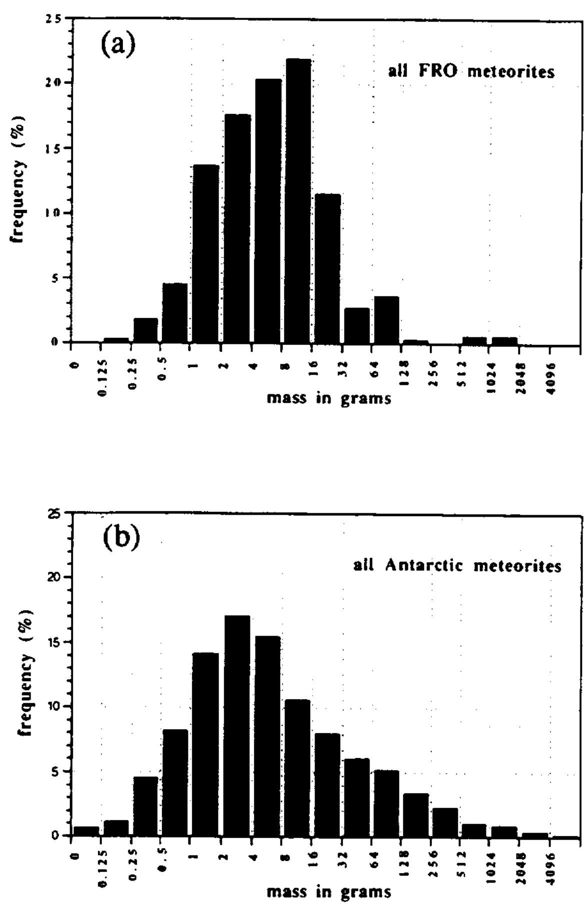

Fig. 2. Mass distribution of (a) all Frontier Mountain meteorites and (b) all Antarctic meteorites [4]. These statistics mainly suggest that some meteorites of masses ranging from ~30 g up to 500 g are still missing at Frontier Mountain.

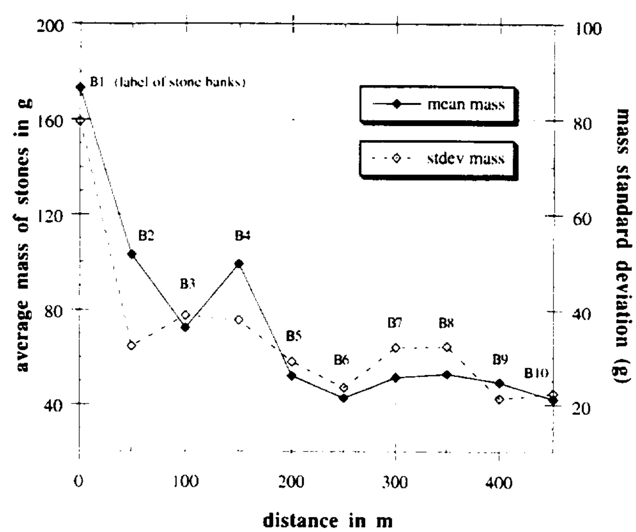

Fig. 3. Plot of the mean values of the stone sizes from different stone banks located on the upwind slope of the ice depression due west of the camp vs. the distance in meters rising uphill from the bottom of the depression along wind direction (NNE). See text for details.

indicate that from the base of the depression toward its upwind flank, in a north-northeast direction, there is a significant reduction in stone size, from average stone weights of 175 g down to 35 g. This size sorting further suggests the eolian origin of the deposit. In addition, it seems that masses smaller than, e.g., 170–250 g are moved on ice surfaces by katabatic winds at Frontier Mountain. This threshold, which has to be confirmed by future controls on the rock races, is almost twice as high as that reported for the concentration site near Allan Hills [6,7], suggesting different wind regimes.

A preliminary geomorphological study of the blue ice field and of the main local moraines was also undertaken.

Although field data are currently being processed, some preliminary observations, based on a first analysis of the aerial distribution of samples in relation to their mass, dynamics of the ice and winds, and local morphology, can be made.

The general scheme for meteorite concentration at Frontier Mountain is that suggested in the previous works [1–5] (Fig.1); however, some new elements emerge, the first of which is the discovery of the accumulation site of large meteorites. Assuming that masses smaller than 170 g are moved on ice surfaces by katabatic winds at Frontier Mountain as discussed above, the finding of large meteorites would decrease the margin of error in identifying meteorite emergence sites for the blue ice field. It is interesting to note that the strip of blue ice where large meteorites are found could be the source for the eolian accumulation of small meteorites found on the opposite side of the depression. In fact, since the direction of prevailing winds is 20°–40° toward the northeast, this area subtends the strip of windblown stone accumulation.

Another interesting hypothesis is in regard to the continued "productivity" of the moraine of the Meteorite Valley. Forty-one meteorites were found in this valley in 1984–1985, 49 in 1990–1991, and 27 this season. Assuming that this area was carefully searched, it would seem that this accumulation zone has a recharge of 8–9 meteorites/yr. This would also imply that the moraine has surprisingly only been accumulating meteorites for 13–14 years! Assuming this order of magnitude is correct, the accumulation in the moraine would have formed within a time span of some decades or at least a few hundred years. This hypothesis might be in favor of a mechanism that reexhumes a "fossil accumulation."

There is another element to be considered. A first analysis of data regarding ice flows and the morphology of Frontier Mountain suggests that the depression in the ice represents the collision boundary of the two ice streams that flow around Frontier Mountain (Fig. 1). Assuming that the eolian accumulation of meteorites on the northern flank of the depression comes from a source to the south-southwest on its southern slope, the distribution of finds suggests that all the Frontier Mountain meteorites come from the southern ice stream only. Furthermore, assuming that a thorough search has been made, it seems that in the northern ice stream conditions for meteorite emergence either do not exist, or there are no suitable conditions for their accumulation.

As yet, all our conclusions are tentative and require further analysis of the current data and quantitative values on ice flow vectors, ablation rates, and the dynamics of eolian transport, to be obtained through regular annual controls in the future during visits to Frontier Mountain. Sub-ice topography, a fundamental factor controlling the dynamics of ice, also needs to be defined. Transepts are required downstream and upstream of Frontier Mountain, to supplement the only existing radar profile running for 6 km from the Meteorite Valley in an east-northeast direction, in order to have a better description of the basement's morphology and ice thickness.

Acknowledgments: We wish to thank M. Frezzotti (CRE-ENEA, Roma) for providing us with important data from his study of satellite images. EUROMET is financed by the EC through its Science (Twinnings and Operations) Programme, Contract No. SCI*-CT91-0618(SSMA).

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AN EVALUATION OF THE METEORITE POTENTIAL OF THE JIDDAT AL HARASIS AND THE RUB AL KHALI REGIONS OF SOUTHERN ARABIA. I. A. Franchi[1], G. Delisle[2], A. J. T. Jull[3], R. Hutchison[4], and C. T. Pillinger[1], [1]Department of Earth Sciences, Open University, Milton Keynes MK7 6AA, UK, [2]Bundesanstalt für Geowissenschaften und Rohstoffe, D3000 Hannover 51, Germany, [3]NSF Arizona AMS Facility, University of Arizona, Tuscon AZ 85721, USA, [4]Department of Mineralogy, Natural History Museum, Cromwell Road, London SW7 5BD, UK.

Over the years there has been considerable success from organized meteorite search programs in hot desert areas of the world, such as the Nullarbor Plain in Western Australia [1], Roosevelt County in New Mexico [2], and Reg el Acfer and Tanezrouft in Algeria [3]. However, the discovery of new areas is important if our meteorite collections are to continue to grow as the rate of return from these existing areas diminishes or access becomes problematic or commercial exploitation becomes dominant. Therefore, this paper is an evaluation of the potential of areas in the southeastern part of the Arabian peninsula for any meteorite recovery program.

Two areas stand out as having yielded relatively high concentrations of meteorites: Jiddat al Harasis, a large sand and gravel plain in central/southern Oman, and the Rub al Khali, a huge sand sea in southern Saudi Arabia. Both areas are extremely sparsely populated, yet 24 meteorites have previously been found in this region (Fig. 1). Indeed, the observation of relatively large numbers of

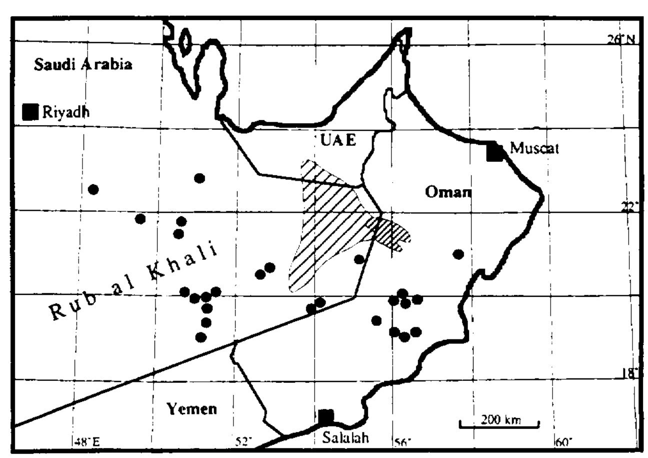

Fig. 1. Map of the southeast portion of the Arabian peninsula showing all meteorite finds in the Rub al Khali and Jiddat al Hirasis. Also shown is the extent of the large playa and the larger area of playa exposed in interdune areas.

meteorites was first commented upon by Holm [4]. Five of the meteorites were found in the early 1930s during the first crossings of the area by Europeans, and almost all the remainder were recovered after opening up of the region to oil prospecting operations in the 1950s and 1960s. The Arabian peninsula has generally been arid since the start of the Pleistocene and hyperarid since about 17,000 BP [5]. On the basis of the meteorite concentrations, the arid climate, and the sparse human population, a six-day reconnaissance of the Jiddat al Harasis by the first two authors of this paper was conducted as part of the EUROMET program in October 1993. During this reconnaissance, two additional samples were recovered.

The Jiddat al Hirasis is an area of about 60,000 km^2 with an average altitude of about 200 m above sea level (Fig. 1). The terrain is predominantly composed of Oligocene/Miocene gray/buff limestones and marls with some chalks. The sediments are almost flat lying, with a very gentle dip of about 6° to the north. The effect of this northward dip is to create an internal drainage pattern, resulting in a number of playa deposits across the region. The total variation in relief is no more than a few tens of meters with very gentle inclines, although occasionally small broken scarps have developed. The surface of the plain is variable in nature, ranging from quite blocky limestone rubble (angular fragments up to 15 cm) to coarse sand/gravel soils to chalky sands, and ranging in color from gray through brown to white. The number of dark stones present on the surface, a key factor in determining the probability of identifying a meteorite, was generally fairly low. There is no apparent major sediment input into the plain, although wind sometimes blows from the north and transports sand from the Rub al Khali. Many of the surfaces appeared to be ablation surfaces, either stripped of soil or with concentrations of stones on the soil surface. Vegetation ranged from sparse grasses and occasional small trees in the southeast to essentially none in the west and the north (with the exception of wadis).

During the six days in the field, eight different localities were searched, usually by foot, sampling a range of different terrains all the way across the region (Fig. 2). Logistics in this region were very straightforward due to the Muscat-Salalah highway running through the north of the region, with a number of well-maintained (but incompletely mapped) graded roads servicing the various oil production facilities. The two meteorites found during the reconnaissance trip were 1.75 kg and 0.4 g and have been tentatively classified as H4 and L7 respectively. The larger sample is quite weathered and was recovered as 20 fragments spread over ~2 m. The similar degree of weathering and the proximity to one of the known Jiddat al Harasis stones (Fig. 2) strongly suggest that this may in fact be part of the same fall. Due to the small size of the second meteorite and the lack of positional information about the Hajmah finds, it is difficult to determine whether this sample is also paired. Overall, this area showed considerable promise as a possible meteorite search area; a further test of its fruitfulness will be conducted with a larger party with more concentrated searching. However, the intense oil exploration and production activity over the past 40 yr has left much of the ground thoroughly covered in tire tracks, perhaps suggesting that some meteorites in the area may have already been collected. As an example, within a 20-m radius of the large meteorite, there were nine sets of tire tracks, perhaps indicating that most of the vehicles were either driving too fast to spot meteorites or were not interested in small dark stones.

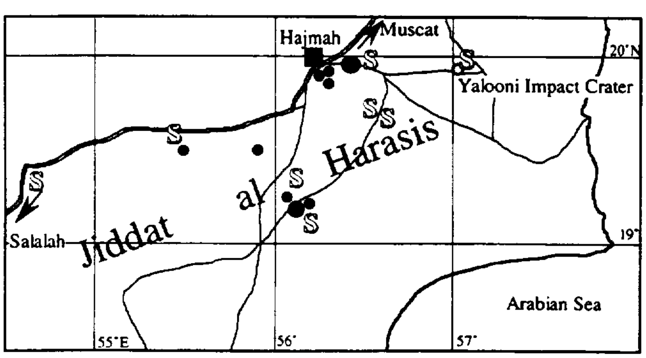

Fig. 2. Map of meteorite locations and search areas on the Jiddat al Harasis. Meteorite locations are shown with shaded circles (larger circles show position of new finds). Search areas are shown with a large S. The locations of the three meteorites around Hajmah are not accurately known; their given positions are those of the oil camp where they were first identified as meteorites. Similarly, the most westerly meteorite is also poorly referenced.

The Rub al Khali is the largest sand sea (~550,000 km^2) on the planet and currently one of the most arid. Although initially such an area would not normally be considered as a potential meteorite-bearing region, the number of meteorites relative to the total number of people in (or who have crossed) the area suggests that more meteorites exist there. The question is, how many more? Many of the meteorites that have been recovered from this area have been rather badly weathered, suggesting either long terrestrial residence times or poor preservation conditions. At the eastern end of the Rub al Khali is a large playa deposit (~3500 km^2) with extensions in interdune areas extending up to 200 km further west (Fig. 1). Although this area was hyperarid or arid for most of the Pleistocene, there have been some periods of more humid conditions [5] during which there would have been development of the playas. Obviously, the presence of saline water, even for short periods, could greatly accelerate the weathering of any meteorites. However, a preliminary survey of terrestrial ages on the Rub al Kahli and Jiddat al Harasis meteorites (Table 1) displays a range of ages from 6400 to 31,100 yr. This range is comparable to other desert meteorite collections [6], and although the meteorites from this area probably are somewhat more weathered, this does not appear to have significantly affected their probability of preservation.

Satellite images show that there are large tracks of interdune areas (several kilometers wide by tens of kilometers long), particularly in the southern parts of the Rub al Khali, where it would be straightforward to conduct systematic searches. It would also be

TABLE 1. ^{14}C terrestrial ages (method as in [7]) of meteorites from Jiddat al Harasis and Rub al Kahli.

Jiddat al Harasis		
Hajmah (a)	Ureilite	18,300 ± 1,700
Hajmah (c)	L5–6	15,200 ± 1,300
Tarfa	L6	15,200 ± 1,300
Jiddat al Harasis	H4	31,100 ± 2,300
Rub al Khali		
Suwahib (Adraj)	L4	6,400 ± 1,300
Suwahib (Ain Salah)	H6	27,500 ± 1,600

interesting to establish whether the very large and relatively stable dunes in this region have produced any local meteorite concentrations. However, due to the remoteness of this area and the difficulty of crossing sandy terrain, there are many logistical and some political problems associated with attempting to operate in this region.

Acknowledgments: EUROMET is indebted to H. Al Azri at the Ministry of Petroleum and Mines and R. Daly at the Office of the Advisor for Conservation of the Environment, in Muscat. We are also very grateful for the help of N. Winser at the RGS in setting up all the necessary connections. EUROMET is is supported by the EC through its Science (Twinnings and Operations) Programme, Contract No. SCI*-CT91-0618(SSMA).

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METEORITE FIND LOCATIONS, SHOCK CLASSIFICATION, AND PAIRING OF 464 METEORITES FROM THE SAHARA AND THE MINERALOGICAL AND CHEMICAL CHARACTERIZATION OF RARE TYPES.

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Four hundred seventy meteorites were collected between 1989 and 1993 mainly from the Algerian part of the Sahara. Four hundred sixty-four samples have been studied at the Institute of Planetology in Münster; some samples were sold by the finder before classification and were not available for study. The most important find locations of these samples are given in Fig. 1a. In addition, the location of the Daraj area is included, where 54 meteorites were recovered in the past. Most meteorites (319) were found in the Acfer region, which is about 30 × 100 km in size (Fig. 1b). While the masses of most meteorites from Antarctica, Roosevelt County, and the Nullarbor Plain are on the order of 10–100 g, meteorites found in the Sahara are generally larger. Most meteorites weigh between 100 and 1000 g (Fig. 2).

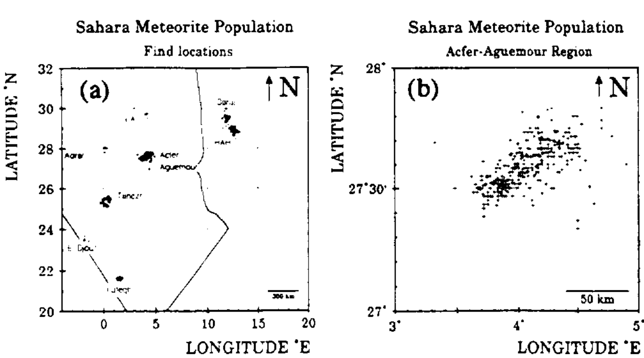

Fig. 1. (a) Main find locations in the Sahara; EA = El Atchane; Tanezr. = Tanezrouft; HAH = Hammadah Al Hamra. (b) Meteorite finds in the Acfer-Aguemour region.

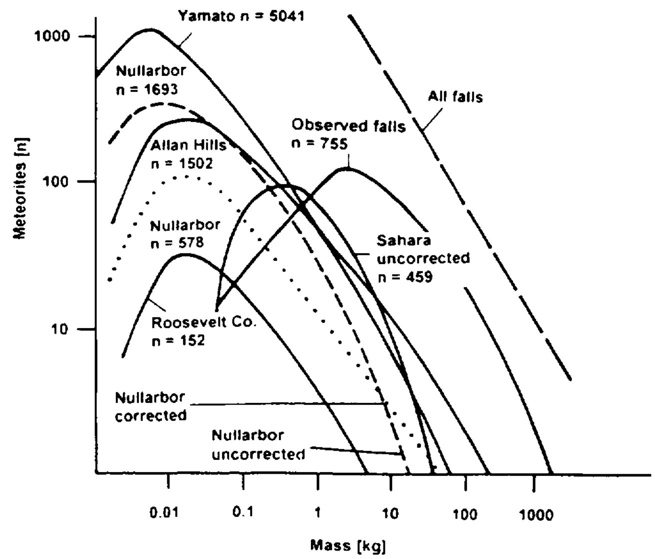

Fig. 2. Number of meteorites vs. mass of meteorite falls and finds from different areas (after [14,16]).

If pairing is not considered, 433 ordinary, 21 carbonaceous, and 3 enstatite chondrites occur among the 464 meteorites. One meteorite belongs to the new group of Rumuruti (R) chondrites [1,2]. In addition, one ureilite, three mesosiderites, and two iron meteorites were identified. We have tried to solve the pairing problem by considering the find location, the degree of weathering, the degree of shock metamorphism, and the mineral chemistry (olivine, pyroxene). In Table 1 the number of meteorites of different meteorite classes and their frequency distributions are listed, along with the frequencies of meteorite falls and finds from Antarctica and the Nullarbor desert. The distribution of the 297 ordinary chondrites in various classes (H, L, LL) and petrologic types (3–6) is given in Table 2.

The degree of shock metamorphism of the stony meteorites was obtained according to the classification system of Stöffler et al. [3]. The results for the ordinary chondrites are given in Fig. 3.

Of the 21 carbonaceous chondrites, 12 belong to the CR chondrite Acfer 059/El Djouf 001 [4], and 3 samples to the CH chondrite Acfer 182 [5]. All others are unpaired. Thus, eight carbonaceous chondrites are among the set of meteorites from the Sahara.

TABLE 1. Number and frequency (%) of meteorites from the Sahara (corrected for pairing) and other locations [15].

	Sahara Finds n = 315		Nullarbor Finds n = 107	Antarctica Finds n = 1100	World Falls n = 835
Chondrites	309	98.1%	93.4	91.3	86.2
Ordinary	297	94.3%	87.9	87.9	80.0
Carbonaceous	8	205%	4.6	2.7	4.6
Enstatite	3	1.0%	0.9	0.7	1.6
Rumuruti	1	0.3%	?	?	~0.1
Achondrites	1	0.3%	2.9	5.8	7.9
Mesosiderites	3	1.0%	0.9	0.7	1.1
Irons	2	0.7%	2.8	2.2	4.8

TABLE 2. Classification of ordinary chondrites from the Sahara (corrected for pairing).

Type	3	4	5	6	Σ
H	27	32	81	32	172
L	10	8	23	61	102
LL	2	4	10	7	23
Σ	639	44	114	100	297

Rare Meteorite Types: Acfer 182 is chemically, texturally, and mineralogically similar to Allan Hills 85085 [5] and Pecora Escarpment 91467 [6]. Considering their affinity to carbonaceous chondrites, their high bulk Fe content, and their high metal abundance, they were designated as CH chondrites [5]. Grossite is a very abundant phase in CAIs from Acfer 182 [7,8]. Acfer 217 has chemical and mineralogical properties very similar to Rumuruti and Carlisle Lakes [1]. It is a regolith breccia with abundant olivine (~72 vol%) that has a high Fa content of 37–39 mol%. With the meteorite Rumuruti, the first fall of this type of chondrite (eight members) is known; therefore, this group has been designated as the R chondrites [2]. Acfer 094 is a uniquely primitive carbonaceous chondrite that has more diamond and SiC than any other specimen studied [9]. Based on the mineralogy, chemistry, and O isotope characteristics, it is not possible to unambiguously distinguish the meteorite between CO3 and CM2 chondrites. It is suggested that Acfer 094 may be the first CM3 [10]. The other carbonaceous chondrites from the Sahara were briefly characterized [11]. Also, the ureilite Acfer 277, the H3–6 chondrite regolith breccia Acfer 111 [12], and the EL-chondritic melt rock Ilafegh 009 [13] are of great interest for meteorite research.

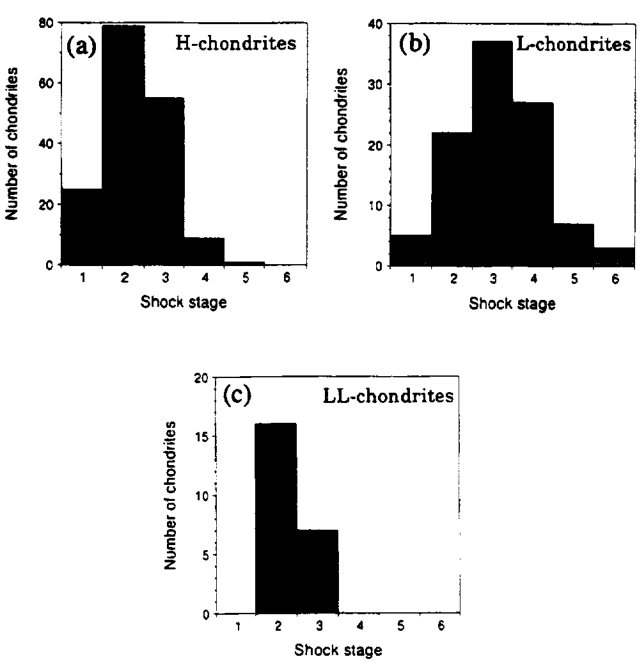

Fig. 3. Shock classification of ordinary chondrites from the Sahara; data are corrected for pairing.

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THE 1993 EUROMET/MONGOLIAN EXPEDITION TO THE GOBI DESERT: SEARCH FOR METEORITES.

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The Gobi Desert in central Asia is one of the largest deserts on Earth. It is about 2000 (west-east) × 1000 (north-south) km in size and is located in southern Mongolia and northern China. Based on scientific contacts between the University of Hamburg and the Mongolian Academy of Sciences, a plan for a EUROMET meteorite search expedition with the Academy of Sciences of Mongolia was worked out in 1992. The expedition started on August 28, 1993, in Ulaanbaatar and lasted through September 13.

The route of the expedition is given in Fig. 1 Ulaanbaatar–Mandal Gobi–Tugalin Bulen–Dalanzadgat–Chinese Border–Tabun Khara Obo–Sainshand–Airag–Ulaanbaatar. The central part of the Gobi Desert is located south of Dalanzadgat and belongs to the variscian South-Mongolian zone. One of the characteristics of this zone is the abundance of rocks derived from basic volcanic explosions in the Silurian and Devonian period in combination with deep-sea cherts and rocks of the ophiolite association. The platform cover from Upper Cretaceous to Cenozoic consists of coarse-grained molassic red-colored sediments, effusive basaltic rocks, and gravels and sands. The expedition spent most of the time in these areas searching for locations with light-colored surface rocks without dark volcanic constituents. Since geologic mapping for most areas exists only on a 1:1,000,000 scale, it was quite impossible to find appropriate areas for meteorite search. A small airplane was chartered to get some more information about the Mongolian part of the Gobi Desert. Indeed, some areas were found that appeared to be interesting for search activities (Borzougiin and Galbien Gobi). For several days, these areas were scanned by seven people on foot. In addition, some search was performed by car, but no meteorites could be found.

Why were Meteorites not Found? The expedition in the Gobi Desert was faced with one severe problem. The summer of

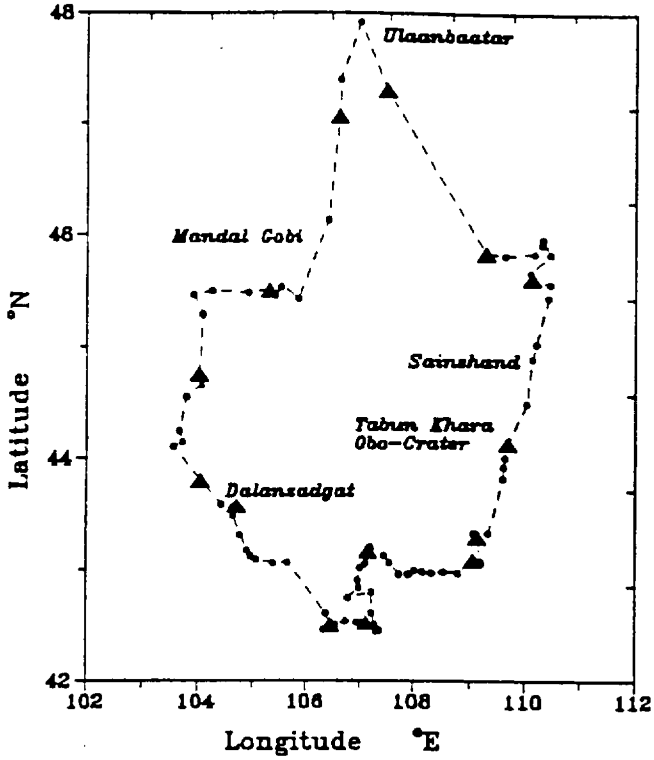

Fig. 1. Route of the reconnaissance meteorite search in Mongolia. Positions taken by a GPS instrument are given by small dots; indicated are a few villages as well as the impact crater Tabun-Khara-Obo. Triangles are campsites.

1993 was one of the wettest in the Gobi Desert in the last 50 years. Thus, it was not possible to reach all areas of interest because there was too much water in some rivers that were normally easy to cross. Also, the desert was "green," with lots of vegetation. This unusual abundance of vegetation led to another problem: Thousands of antelopes and khulans (a type of wild horse) had moved south (into the normally dry area), causing black "fall-out" everywhere.

On the other hand, as stated above, volcanic rocks occur in many locations of the Mongolian desert. The occurrence of black volcanic rocks within the sediments makes the recognition of meteorites almost impossible. We only found small areas without these black rocks from volcanic activity. Based on many dried water streams in the Gobi Desert, we believe that heavy rain occasionally falls, changing the morphology of the surface and reworking the surface sediments. In addition, typical heavy winds help to modify the upper meters of the sediments. Thus, it may be very difficult to find very old unprocessed areas.

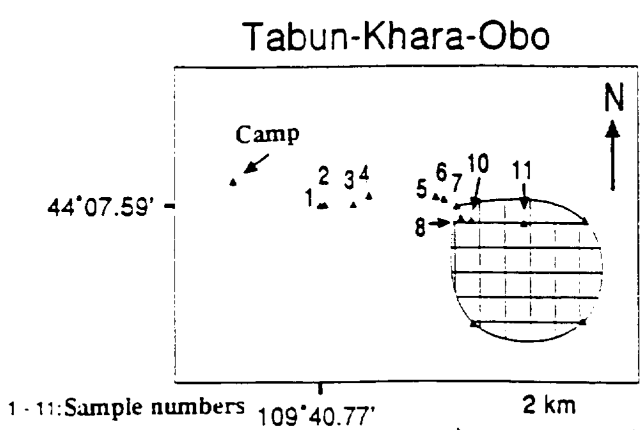

Fig. 2. The Tabun-Khara-Obo Crater in Mongolia.

Tabun-Khara-Obo Crater: The expedition passed the Tabun-Khara-Obo Crater, which is located in southeastern Mongolia about 470 km south-southeast of Ulaanbaatar and 95 km south-southwest of Sainshand. Based on Landsat I photographs, McHone and Dietz [1] described the impact crater as a 1.3-km (diameter) sand-filled crater with a high degree of circularity. It is suggested that the crater is about 1 m.y. old. The elevation of the wall crest above the bottom of the depression is on average 20–30 m and reaches a maximum in the east of 50 m [2]. Microschists and diorites within the wall are intensely deformed. Breccias occur in the form of lenses mainly within the inner crater wall and are several meters thick. A block of fine-grained, fragment-rich impact melt was found inside the crater.

Some breccias were also found outside the crater up to ~500 m from the crater rim. Positions of the highest elevations (four positions) of the crater rim were taken by GPS. Based on these measurements, the crater is certainly larger than 1.3 km in diameter and probably close to 1.8 km in diameter (Fig. 2). A profile of samples was taken from Tabun-Khara-Obo Crater. At 11 positions about 60 samples of the representative rocks were collected (Fig. 2). A study of these rocks is in progress.

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CURRENT RESEARCH ACTIVITIES OF ANSMET: 1. RECENT STUDIES IN THE WALCOTT NÉVÉ REGION; 2. PLANNED FUTURE ACTIVITIES. R. P. Harvey, Department of Geological Sciences, University of Tennessee, Knoxville TN 37996-1410, USA.

Recent Studies in the Walcott Névé Region: The 1993–1994 Antarctic field season to the Walcott Névé region was the seventeenth overall for ANSMET (the Antarctic Search for Meteorites project, funded by the Office of Polar Programs of the U.S. National Science Foundation). The 1993–1994 season marked the third led by the author, the eighteenth season for co-P.I. W. A. Cassidy, and the twelfth season for co-I. J. W. Schutt, who served as mountaineer and safety officer.

The Walcott Névé region has been a prolific source of meteorites for ANSMET field parties, including well-known meteorite sources such as the Lewis Cliff ice tongue and the MacAlpine Hills ice fields. This season's research efforts were twofold. The goal during the first part of the season was to collect ice samples and radio echo-sounding data from the Lewis Cliff ice tongue, in an effort to understand the glaciology of that stranding surface. The second was to systematically search for meteorites in an area informally called "Foggy Bottom," a set of unnamed nunataks at the southeast end of the Walcott Névé that had been visited previously for reconnaissance purposes and had not been systematically searched.

During the first 10 days of the season, radio echo-sounding traverses down the length of the Lewis Cliff ice tongue and across it were performed to develop a crude three-dimensional model of the basement below the stranding surface. In addition, many previously installed surveying stations were resurveyed in support of continuing ice-movement studies of the ice tongue. Finally, near the northern end of the ice tongue, exposed volcanic dust bands suggest a tilted stratigraphic sequence in the ice. A 50-m channel sample was cut at the ice surface, perpendicular to the suspected time-stratigraphic sequence. This sample has been subdivided and distributed to various ice chemistry specialists, with the hopes of identifying the specific time sequence exposed by comparison to established ice chemistries from core studies.

At the completion of this glaciology research, the field camp was relocated approximately 50 km south of the Foggy Bottom area. Reconnaissance and a short period of systematic searching during two previous seasons had established the presence of meteorites in this region. Roughly 100 meteorites had been recovered in this area, and we estimated another 200–300 might be present, based on similarities to other fields. We were pleasantly surprised, therefore, to find an abundance of meteorites at various localities in the area. Many of these meteorites were found scattered among terrestrial rocks in moraines and on firn near the edges of ice fields. The vast numbers of meteorites did not allow us to complete systematic searching of the area, and thus we are compelled to revisit the region in the near future.

A total of 858 meteorites were recovered during the 1993–1994 ANSMET season. The vast majority of these are ordinary chondrites, and may represent a small number of shower falls rather than a large number of individual falls. However, the several achondrites, carbonaceous chondrites, and metal-rich meteorites recovered should prove to be of significant interest to scientists. The most important meteorite find of the season was a single lunar specimen, similar to those found at MacAlpine Hills about 70 km away.

The recovery of Antarctic meteorites continues to stimulate meteoritical research. As of April 1994, 8813 samples of Antarctic meteorites have been distributed to 260 researchers from 20 nations. A total of 7078 meteorites have been recovered by ANSMET since its inception in 1976. Interest in Antarctic meteorites continues to be high, and nothing is foreseen that would abate the world's desire for more meteorites. As of March 1994, over 55 men and women from 45 different institutions in 16 nations have participated as ANSMET field party members.

Directions for Future Work: Although there are many theories as to why meteorite stranding surfaces exist and how they work to concentrate extraterrestrial specimens, our understanding remains fragmentary. There are many reasons for this; while each stranding surface appears to share a few broad traits, such as high ablation rates and sub-ice obstruction to ice flow, studies of individual ice fields continue to frustrate us with their unique and complex characteristics. Recognizing the complex nature of the problem, we are making efforts to involve scientists from related disciplines in our studies of stranding surfaces. Our recognition of the complexity of meteorite stranding surfaces has also renewed our efforts toward setting up rigorous long-term experiments. During the coming field season we plan to establish a highly controlled, large-area ice movement and ablation network throughout the Foggy Bottom region. This will provide a superb framework for future studies by providing an accurate baseline of local ice flow and removal characteristics. We hope that this first step will encourage other scientists to work with us toward establishing an accurate recent history of the ice sheet for this important area near the head of the Beardmore glacier.

As noted above, the 1994–1995 ANSMET field party will return to the Foggy Bottom area with a group of six. This will be the fourth visit to the area, which has yielded around 1000 meteorites so far. We estimate that there may be another 200–300 meteorites in this region. If time allows, we will also search for meteorites on the nearby Goodwin nunataks ice field, and we hope to traverse to the MacAlpine Hills region, where we can complete previous systematic searching efforts. Late in the season, Twin Otter aircraft will be used during reconnaissance of several ice fields in the region of the Transantarctic Mountains lying between the Darwin and Byrd glaciers. Previously identified ice fields in this region will be searched in detail for the first time since they were first visited in 1977. A two-person party will explore this region for approximately one week, in the hopes of estimating the requirements for future systematic searches. The 1995–1996 season will likely visit other previously identified ice fields further to the south (in the Grosvenor Mountains and Dominion Range region) via Twin Otter aircraft. There is a plan for possible joint operations with the Australian Antarctic Division in 1996–1997.

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MOVING TARGETS: THE EFFECT OF SUPPLY, WIND MOVEMENT, AND SEARCH LOSSES ON ANTARCTIC METEORITE SIZE DISTRIBUTIONS. R. P. Harvey, Department of Geological Sciences, University of Tennessee, Knoxville TN 37996-1410, USA.

The size distributions of Antarctic meteorite collections are influenced by many distinct factors, including the original supply of meteorites from space, losses to weathering and wind movement, and searching techniques. Many of these factors have been modeled, both empirically and theoretically, by previous researchers, usually with regard to geological materials other than meteorites. In this work I will combine new and established models for application to studies of the size distribution for all Antarctic meteorites (AAM) from [1]. The resulting model is dependent on measurable variables and has application to meteorites from other collection sites as well.

Supply: Accepted models for the supply of meteorites to the Earth's surface usually take the form of a power law, based on empirical studies of impact distribution on orbiting spacecraft and studies of mechanical breakage related to impact phenomena [2,3]. The basic premise is that fragmentation events produce an exponential increase in specimens, each of which is exponentially smaller. Power-law distributions consequently take the form of a straight line on a log-log plot of mass (size) vs. cumulative number of specimens (Fig. 1b). As a result, at diminutive sizes the number of small particles can be dramatically large. However, these very small particles are often more susceptible to loss phenomena such as removal by wind, further breakage, and search inefficiencies, as

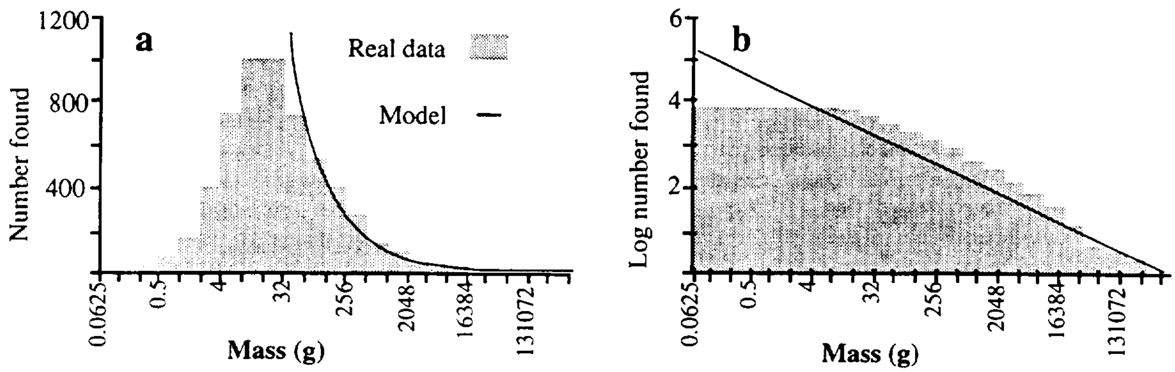

Fig. 1. Size distributions for the AAM dataset (n = 5715). (a) The size distribution plotted with a nonlogarithmic count of specimens along the vertical axis, and a series of mass bins, doubling in size to the right, on the horizontal axis. (b) The same dataset plotted with a cumulate-log vertical scale. The power law shown was fitted to all meteorites larger than 64 g and an X intercept equal to the size of the largest AAM meteorite (407 kg).

discussed below. Past researchers have considered this when fitting power laws to observed meteorite size distributions at the Earth's surface, constructing their models from the very largest fragments—the majority of the mass but a minority in number [4–9]. Unfortunately, these power-law models then become extremely sensitive to the slope of a line modeled from very few accurately known data points [1,10,11].

Weathering: Fragmentation due to weathering and abrasion processes such as frost wedging, salt production, wind abrasion, chemical exsolution, and biological actions [12] also contribute to the number of specimens ultimately found on a stranding surface. The vast majority of meteorites from Antarctica exhibit significant weathering features, even those found still enclosed in ice [13–17], due to exposure to saltating snow and ice particles, long-duration freeze-thaw cycles, and evaporite formation [15,18–20]. Most empirical fragmentation models produce bell-shaped size distributions with a maximum where a rock has been reduced to a collection of resistant mineral fragments. While such distributions show a good empirical fit to the AAM dataset, they do not incorporate the initial power-law supply commonly accepted, and controlling variables often are not physically measurable. Theoretical models of fragmentation, however, are easily incorporated into a modeled power-law supply by increasing its slope. The model presented here defines the combined supply and fragmentation power law with two variables. The X intercept is the mass of the largest observable meteorite; for Antarctica this is roughly 400 kg. The power-law slope defines how many meteorites of sizes smaller than the X intercept are found; literature values vary between 0.7 and 1.2 [8]. Figure 1 shows a typical power-law fit to the AAM dataset as used to formulate the combined model.

Wind Loss: Like weathering, wind movement of particles has been extensively modeled under conditions appropriate to desert and polar environments (see [21–24] for summaries). These models, both empirical and theoretical, attempt to formulate the wind velocity necessary to initiate particle movement given various conditions of air density, particle size, adhesion and frictional forces, and surface conditions. Although these models can become quite convoluted, Antarctic meteorites present a very tractable problem by virtue of their resemblance to an ideal physical model. Meteorites generally are well exposed to the wind, are roughly spherical bodies

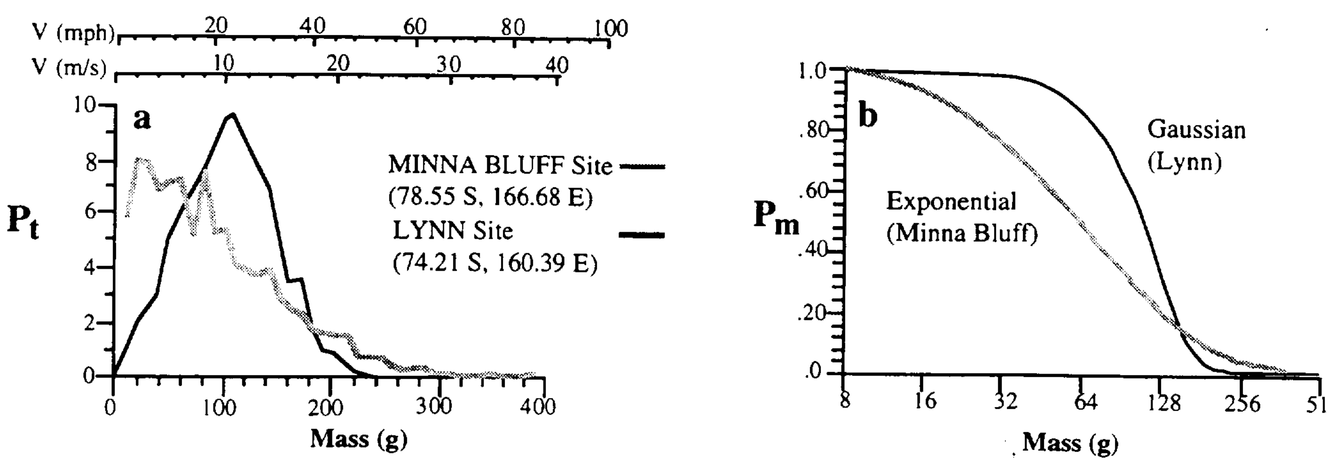

Fig. 2. Probability of threshold velocity occurrence in Antarctica. (a) Measured wind velocities at two sites along the Transantarctic Mountains during 1992. P_t is the percent of time winds of various velocities were recorded. (b) Exponential and gaussian curves fit to the data from (a), plotted as probability of threshold velocity occurrence (P_m) in a given year vs. mass. Note that although winds of higher speeds occur in the exponential regime, particles with masses < 200 g have a higher probability of moving in a gaussian regime.

lying on a relatively frictionless, level plain, and complicating factors such as the vertical wind profile, Sun-cupping, and pedestal and wind-scoop formation are easily incorporated into the formulation of the relation between meteorite size and the threshold wind speeds necessary to establish movement. Annual wind-velocity distributions are available for several locations on the East Antarctic plateau [25]. These wind-velocity distributions take two general forms: an exponential form, where high winds are relatively rare but milder winds are omnipresent, and a gaussian form, where an intermediate windspeed is most common (Fig. 2a). Knowing the probability of a windspeed's occurrence during a given year and calculating the size of meteorite that wind can move yield a relatively simple relationship between specimen size and the probability of particle movement. As expected, the probability that a particle will move is strongly anticorrelated with size. Larger particles have a low probability of threshold movement, and thus while they may occasionally be in motion, it should be a relatively rare event. Small particles have very high probabilities of encountering threshold wind velocities, and may effectively be in constant motion, greatly increasing their likelihood of leaving meteorite search locations. The model presented here calculates the probability of particle movement based on a choice of either exponential or gaussian windspeed distribution, the mean and variance of wind speed, and threshold velocity variables as discussed above. The number of meteorites within each bin of the size distribution is then reduced by the probability those meteorites would move during a single year. This assumes that particles with 100% probability of movement during a single year are certainly lost over a longer time period.

Searching Efficiency: As in the case of wind losses above, meteorite collection presents a very tractable modeling problem; we look for dark, relatively large objects on a plane of limited area. Meteorite searches usually involve a series of transects of a suspected collection area, with a definite spacing between searchers and systematic coverage of an entire region. Empirical models exist for analogous searches, such as those used to estimate whale populations in the ocean, traffic flow on highways, and deposition of garbage around receptacles [26–30]. For this study, a theoretical model has been developed, based on common transect search techniques and models of human visual acuity.

Visual acuity is defined as the ability of an observer to visually distinguish objects from background under perfect conditions, such as a bright light on a dark background, or vice versa. The average person can detect objects with an angular size of about 2 min of arc. Because the ability to detect a target is controlled by angular dimensions rather than true size, acuity defines an inverse geometric relationship between the size of an object and the distance at which it is visible; i.e., the farther away something small is, the harder it is to see. Assuming that targets are randomly distributed within a transect of known width, the likelihood that a target of a given size will be found can be calculated. Simulated searches based on these principles, incorporating conditions specific to ANSMET search procedures (linear, partially overlapping transects of an entire ice field), suggest that meteorites smaller than approximately 8 g are more likely to be lost than larger specimens (Fig. 3). In addition, the probability of even the smallest specimens is never zero, because it may fall directly in the center of the search transect. For the combined model the calculated probability of particle loss due to searching is applied to the initial supply after wind losses have been incorporated.

Combined Model/Conclusions: In the combined model the supply functions are treated as a background of meteorite specimens upon which the loss phenomena are immediately superimposed. For most Antarctic ice fields this is probably an accurate description of the meteorite collection process. The vast majority of meteorites appear to have resided on stranding surfaces for tens of thousands, if not hundreds of thousands, of years, while wind losses occur on a yearly basis and searching occurs over a period of weeks [31].

Figure 4 is a comparison of the combined model and AAM size distributions. The model mimics the observed distribution quite well, within nominal statistical significance. The combined model is the product of a tremendous number of variables with varying influence on the results. Of these variables, it appears that power-law slope, intercept, and the wind speed distribution are most important. In addition, although most simulations run to date provide a single best-fit model, it is not apparent that any single solution is unique. As a result it is not prudent to assume that the model can be used to infer that the values chosen for these variables are valid, or used to calculate an age for the ice surface. However, the ability

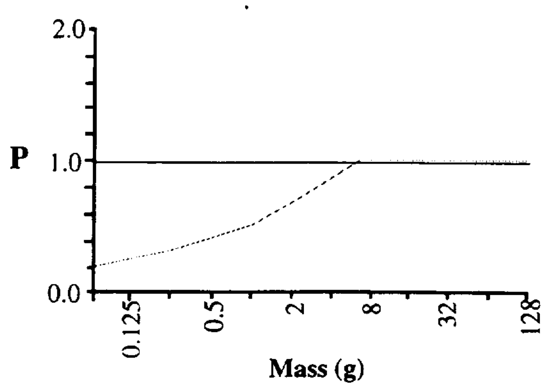

Fig. 3. Probability of search loss vs. specimen size for typical values of visual acuity (2 min of arc) and Antarctic search conditions (transect width of 30 m). Note that specimens larger than ~8 g are always found, and P never reaches 0 for the smallest specimens.

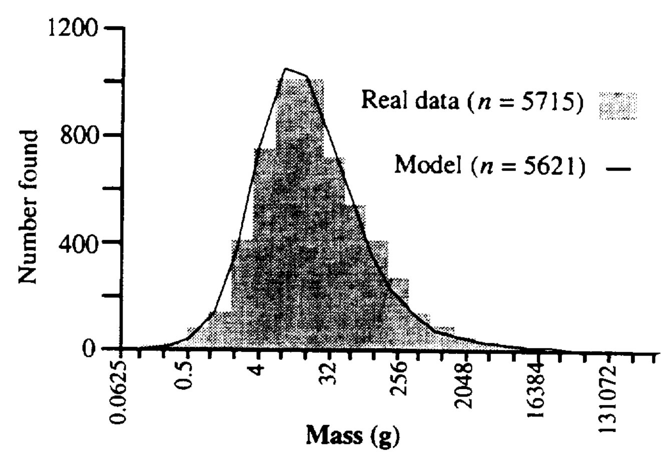

Fig. 4. Example results from the combined model. Values for some of the key variables are as follows: Largest observed meteorite is 3007 kg, power-law slope is −1.15, wind regime is gaussian, mean velocity is 1.1 m/s at surface, and surface roughness is 5 cm.

of the model to produce size distributions similar to those observed does suggest that the various supply and loss phenomena do interact in the manner described above. In addition, the strong dependence of the model on the variables describing power-law supply (presumably a measure of the age of the ice field) and local wind speed distributions suggest that these factors have a great deal of influence on the size of meteorites that will be found on an ice field.

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CARBON-14 TERRESTRIAL AGES AND WEATHERING OF METEORITES FROM THE NULLARBOR REGION, WESTERN AUSTRALIA.

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A meteorite's terrestrial age [1–3], or the time it resides on the Earth's surface, is important in determining the history of the meteorite. Carbon-14 was originally used for large samples, but for the last 10 years, smaller samples of meteorites of 0.1–0.5 g have been dated using accelerator mass spectrometry [2–5]. The precision of terrestrial age estimates is limited by the accuracy to which the saturated activity of ^{14}C in the meteorite is known, and the production of ^{14}C can vary with the depth and size of the object. Carbon-14 as a function of accurate depth is known for the L5 chondrite Knyahinya [6]. We have used Knyahinya, Bruderheim, and some other chondrites to establish a saturated activity reference level of about 51 dpm/kg for L chondrites [3,6]. The storage time before a meteorite weathers away is much less for warm, arid regions than in some areas of Antarctica, and ^{14}C ($t_{1/2}$ 5730 yr) is the ideal radioisotope to use for estimates of terrestrial age.

As weathering gradually destroys meteorites in a given population, the resulting distribution for similar types of meteorites should be an approximately exponential decrease of meteorites with increasing age. Boeckl [7] determined a "weathering half-life" of some 3500 yr for chondrites from the southwestern U.S., but a later reinvestigation of this study [3] determined that the ^{14}C age distribution of the meteorites was longer.

We have studied ^{14}C ages of meteorites from Roosevelt County, New Mexico [8], the western Libyan desert [5], and Algeria [9]. In these areas meteorites as old as >40,000 yr are observed, and the mean survival time at these locations is well over 10,000 yr. For 13 meteorites from the Hammadah al Hamra, Libya, Jull et al. [5] found a break in the age distribution that might be related to the timing of climatic changes in the collection area. The Roosevelt County collection also shows departures from exponential behavior, possibly due to storage of the meteorites in Quaternary cover sands in the area [8].

More than 3.8 million km^2 of Australia is arid or semiarid land that provides conditions for the prolonged preservation of meteorites [10,11]. Two areas in particular have been recognized as areas containing high accumulations of meteorites, and Bevan and coworkers [10–13] have documented large numbers of finds in the Nullarbor Region of Western Australia. In this paper, we have studied the ^{14}C age distribution of over 20 meteorites from the Nullarbor Region.

Figure 1 presents the ^{14}C age distribution of Nullarbor samples compared to some other arid locations where a substantial number of ^{14}C ages have been obtained. The Western Australian meteorites

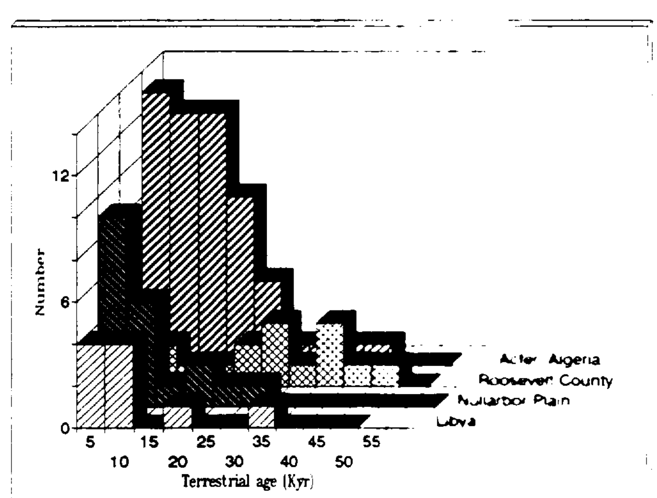

Fig. 1. Distribution of ^{14}C terrestrial ages from Western Australia and other arid regions.

TABLE 1. ^{14}C terrestrial ages of meteorites from the Nullarbor Plain, Australia.

Sample	^{14}C dpm/kg	Terrestrial age (yr)
Billygoat Donga, L6	20.5 ± 0.3	7,550 ± 1,300
	20.0 ± 0.2	7,700 ± 1,300
Boorabie 001, H4–5	41.7 ± 0.3	900 ± 1,300
Burnabbie, H5	2.85 ± 0.2	23,100 ± 1,400
Carlisle Lakes 002, H4–5	32.9 ± 0.3	2,800 ± 1,300
Cocklebiddy, H5	36.9 ± 0.1	1,900 ± 1,300
Deakin 001, anomal.	1.9 ± 0.1	27,100 ± 1,400*
Acid residue	2.4 ± 0.4	25,300 ± 1,900†
Forrest 007, H4	30.9 ± 0.3	3,400 ± 1,300
Forrest 009, L6	25.0 ± 0.2	5,900 ± 1,300
Forrest 010, L4–5	5.84 ± 0.09	17,900 ± 1,300†
Acid residue	1.4 ± 0.3	29,500 ± 2,200†,‡
Kybo 001, LL5	42.5 ± 0.3	2,200 ± 1,300
Mulga (north), #417, H6	33.4 ± 0.2	2,720 ± 1,300
Mulga (north), #585, H6	34.4 ± 1.0	2,500 ± 1,300
Mulga (south), H4	4.1 ± 0.2	20,000 ± 1,300
Mundrabilla 002, H5	2.46 ± 0.09	24,300 ± 1,330
Mundrabilla 005, H5	52.2 ± 0.6	recent fall
North Forrest, H5	10.2 ± 0.9	11,980 ± 1,300
Acid residue	11.9 ± 0.3	11,200 ± 1,300
North West Forrest, E6	31.1 ± 0.3	1,720 ± 1,300
Nyanga Lake 001, H3	21.1 ± 0.2	6,500 ± 1,300
Reid 006, H5	33.8 ± 0.5	2,600 ± 1,300
	32.9 ± 0.2	2,840 ± 1,300
Reid 007, L6	23.8 ± 0.2	6,300 ± 1,300
Reid 010, H6	39.3 ± 0.3	1,400 ± 1,300
Reid 011, H3–6	39.5 ± 0.3	1,300 ± 1,300

* L-chondrite composition assumed in the calculation of terrestrial age.

† The sample was treated with phosphoric acid to remove any weathering carbonates.

‡ The first measurement of Forrest 010 released a large amount of C. The acid-treated sample of Forrest 010 indicates that ^{14}C from weathering carbonates was removed during pretreatment.

show a simple exponential dependence of terrestrial age vs. time, and no meteorites of greater than about 30 k.y. age. This is in contrast to the results from the southwestern U.S. [3], Roosevelt County [8], Algeria [9], and Antarctica [14]. One might expect that meteorites would be more well preserved in a very arid, hot climate. However, the lack of very old stony meteorites in the Nullarbor compared to other locations may be solely a statistical problem. Weathering of meteorites in arid regions is expected to be dominated by the availability of moisture, although weathering could be accelerated by the presence of Cl [15]. Episodic heavy rainfall events probably provide the main source of water, which causes weathering.

We have also studied the carbonates in the weathering products of some of these meteorites. These results show that there are some variations in $\delta^{13}C$, and there is a weak correlation of $\delta^{13}C$ and carbonate content with terrestrial age. The expected exponential drop-off of number of meteorites of a given terrestrial age with time indicates the collection area has been substantially undisturbed during at least the last 30,000 yr. This is certainly consistent with the arrested karst geomorphology of the Nullarbor. The surface of the Nullarbor is considered to be eroding slowly [16], and it has probably been generally stable for considerably longer than 30,000 yr. This is not seen in the U.S. meteorite collections from Roosevelt County or northwest Texas. The less-arid and colder high plains of Texas and New Mexico may result in storage of meteorites by burial for longer periods of time. We observe a deficit of "young" meteorites for these areas. In the sample of meteorites analyzed so far, the Nullarbor data show no evidence of selection of meteorites of a particular terrestrial age.

The Nullarbor may prove to be an important area to provide data on the flux of meteorites with time. Although cyclonic winds have moved small fragments, more than 800 fragments of the Mulga (North) shower, with a terrestrial age of 2.7 ± 1.3 k.y., were found in a well-defined ellipse [17]. Concentrations of meteorites, such as in the Nullarbor Region, also provide datable materials of a variety of terrestrial exposure times during the accumulation period. The degree of weathering of meteorites of different ages may allow changes in weathering rates with time and perhaps even some climatic effects to be estimated.

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MEASUREMENT OF THE LONG-LIVED RADIONUCLIDES BERYLLIUM-10, CARBON-14, AND ALUMINUM-26 IN METEORITES FROM HOT AND COLD DESERTS BY ACCELERATOR MASS SPECTROMETRY (AMS).

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Introduction: Cosmogenic nuclides provide a unique record of collision, exposure, and terrestrial histories of meteorites. The determination of terrestrial ages is of particular importance for meteorites that are found in large numbers in hot and cold deserts. In the course of a project to study meteorites from hot and cold deserts, we investigate the nuclides ^{10}Be, ^{14}C, and ^{26}Al in meteorites from Antarctica and from the Sahara. Here we report first results and discuss some aspects of their interpretation on the basis of production rates derived from physical model calculations.

Experimental: Procedures for the separation of ^{10}Be, ^{14}C, and ^{26}Al from stony meteorites and for the preparation of AMS samples were established at Hannover for the first time. The AMS measurements are made at the ETH/PSI AMS laboratory at the ETH

Hönggerberg in Zürich. A separation scheme of Vogt and Herpers [1] for ^{10}Be and ^{26}Al was modified in order to avoid the use of perchloric acid and to improve purities and yields of the BeO and Al_2O_3 products for the AMS measurement [2]. After adding 2 mg Be carrier and 2 mg Al carrier to the crushed meteorite material, pressure digestion by a mixture of HNO_3, HCl, and H_2SO_4 is performed. After evaporating the solution and pressure digestion of the residue with HCl, an aliquot is taken for determination of the total Al by ICP-OES. After this, Fe is extracted by methylisobutylketone. Beryllium and Al are separated by cation exchange (Dowex 50 WX8) and precipitated as hydroxides, which are glowed in quartz crucibles to oxides. The oxides are mixed with Cu for AMS measurement. All steps of the separation scheme were investigated in detail by ICP-OES before meteorites were analyzed.

The quality of the ^{10}Be and ^{26}Al determination was checked by analyzing a number of meteorite falls [2]. The results are in good agreement with literature data. In order to investigate the precision of the analyses, a meteoritic standard was prepared from the LL6 chondrite Dhurmsala. Seventy-four grams of Dhurmsala, split 2/3a, were crushed to a grain size of less than 125 µm. Metal grains (about 1 g) that could not be crushed to this size were removed. The resulting material now serves as an interlaboratory standard for the laboratories at Köln and Hannover. Repeated analyses of this standard yielded detailed information on the uncertainties of the ^{10}Be and ^{26}Al determination (Table 1).

For the determination of ^{14}C, C is extracted from meteorite samples by high-frequency heating and transformed to CO_2. Meteorite samples of about 150 mg are placed in single-use Al_2O_3 crucibles between two high-purity W rods for proper coupling of the high frequency. In a first step, a sample is heated for 30 min to 1000°C to remove terrestrial contamination and weathering products. Then a first fraction of the gas is taken as a control for AMS measurement. Afterward the sample is kept melting for ~2 min at 1700°C. Then the temperature is lowered to 800°C and this temperature is maintained for ~20 min. This second fraction is used to determine the cosmogenic ^{14}C. Both fractions are completely oxidized; the CO_2 is purified and diluted with about 6 mg ^{14}C-free CO_2. Further details of the procedure may be found elsewhere [2]. The reduction of CO_2 to C and the subsequent AMS measurement are made in Zürich. Details of the reduction process and the AMS measurements of ^{14}C can be found elsewhere [3–5].

The ^{14}C analyses were checked by analyzing samples of the Bruderheim chondrite. Specific activities of 9.7 ± 0.4 dpm/kg and

TABLE 1. Contribution of chemistry and AMS errors to the uncertainty of the ^{10}Be and ^{26}Al determination (1 σ) as determined from n analyses of the Dhurmsala standard and comparison of ^{14}C analyses of Bruderheim from [6], [7], and this work.

	Average (dpm/kg)	n	Experimental Error (%) Chemistry	AMS	Total
^{10}Be	21.4 ± 1.1	18	4.7	2.1	5.1
^{26}Al	69.7 ± 3.3	9	3.3	3.4	4.7
Meteorite	^{14}C (dpm/kg)		Reference		
Bruderheim	46.8 ± 1.4		[6]		
Bruderheim	47.6 ± 2.0		this work		
Bruderheim	50.1 ± 0.3		[7]		

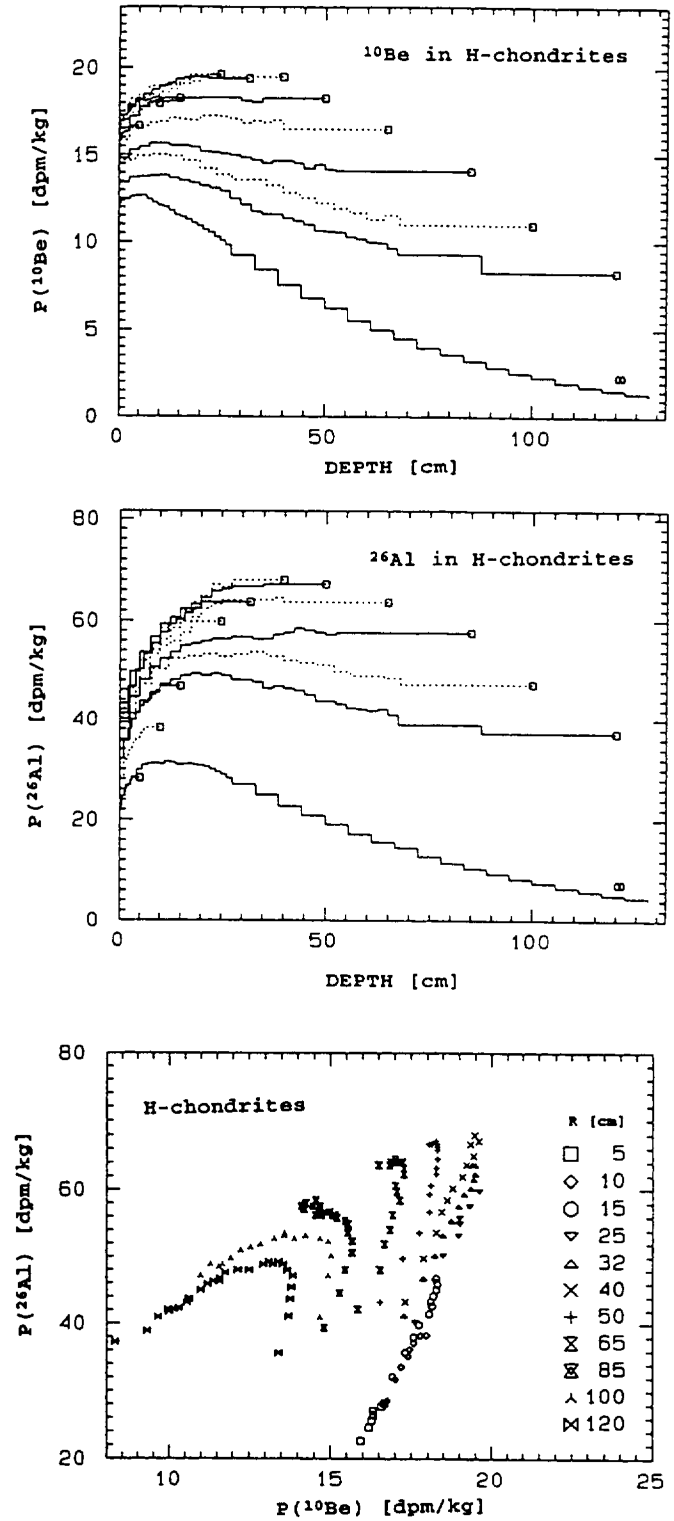

Fig. 1. Calculated production rate depth profiles of ^{10}Be and ^{26}Al in H chondrites (meteoroid radii from 5 to 120 cm and for a 2π irradiation geometry) and correlation between calculated ^{26}Al and ^{10}Be production rates (H chondrites with radii between 5 and 120 cm).

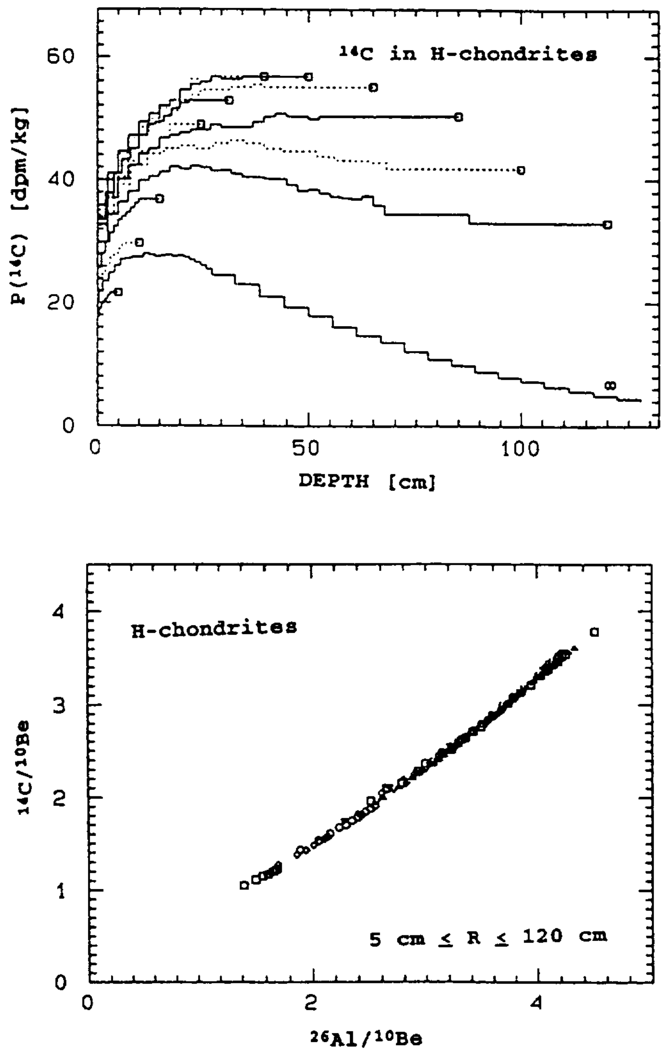

Fig. 2. Depth profiles of calculated ^{14}C production rates in H chondrites (meteoroid radii from 5 to 120 cm and for a 2π irradiation geometry) and three-isotope plot of calculated production rates, ^{14}C/^{10}Be vs. ^{26}Al/^{10}Be (H chondrites with radii between 5 and 120 cm).

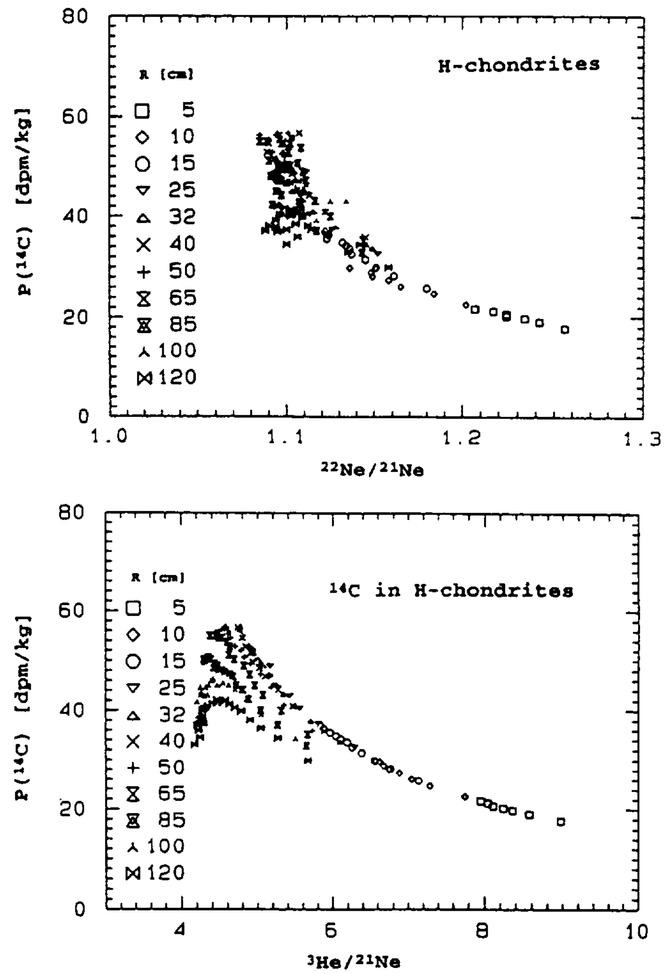

Fig. 3. Dependence of ^{14}C production rates in H chondrites on ^{22}Ne/^{21}Ne and ^{3}He/^{21}Ne production rate ratios for meteoroid radii between 5 and 120 cm.

47.6 ± 2.0 dpm/kg were found in the C fractions taken below and above 1000°C respectively. According to pyrolysis experiments on some ordinary chondrites from the Acfer region (Sahara), performed at the Friedrich Schiller Universität Jena, the fraction above 1000°C can be interpreted as carrying the cosmogenic ^{14}C. The value of 47.6 ± 2.0 dpm/kg lies between the AMS results reported by Jull et al. [6] and by Beukens et al. [7] (Table 1). A ^{14}C analysis of Dhurmsala, split 2/3a, resulted in 53.0 ± 2.3 dpm/kg for the fraction above 1000°C. Our results for both Bruderheim and Dhurmsala lie in the range of ^{14}C concentrations observed in stony meteorite falls, i.e., between 38 dpm/kg and 60 dpm/kg as reported by Jull et al. [6].

Model Calculations: Earlier calculations of depth- and size-dependent GCR production rates by a physical model [8,9] are extended with respect to coverage of cosmogenic nuclides, meteoroid classes, and sizes [10,11]. In this work, we show production rate depth profiles in H chondrites of ^{10}Be and ^{26}Al (Fig. 1) and ^{14}C (Fig. 2). In addition, we present correlations between ^{10}Be and ^{26}Al production rates (Fig. 1), between ^{14}C/^{10}Be and ^{26}Al/^{10}Be ratios (Fig. 2), and the dependence of ^{14}C on ^{3}He/^{21}Ne and ^{22}Ne/^{21}Ne ratios (Fig. 3). The calculations of ^{10}Be and ^{26}Al and of He and Ne isotopes are consistent with recent calculations [10,11]. They represent an improved status as a consequence of the analysis of results from a simulation experiment in which an artificial meteoroid made of gabbro (R = 25 cm) was irradiated isotropically with 1600 MeV protons. The calculations of ^{14}C have a lower quality than those of the other isotopes because of a considerable lack of thin-target production cross sections for proton-induced reactions. Moreover, a validation of the model calculations by analyzing results from simulation experiments is not yet available.

Allan Hills Ordinary Chondrites—Results and Discussion: Beryllium-10 and ^{26}Al were determined in 30 Allan Hills ordinary chondrites from the 1988 campaign (Table 2). Since rare gas measurements are not yet available except for Allan Hills 88019, a final discussion will be postponed until these measurements (which are planned for the near future in Mainz) are made. For 16 of these meteorites measurements of natural thermoluminescence (NTL) were reported by Benoit et al. [12], who proposed pairing of H5: 88025, 88038; H5: 88014, 88040; H5: 88026, 88030, 88033; H5: 88029, 88042. From the results of our analyses there are no objections against a pairing of Allan Hills 88014 and Allan Hills 88040. The lack of correlation between ^{10}Be and ^{26}Al makes it hard to

TABLE 2. Cosmogenic radionuclides in 30 Allan Hills ordinary chondrites from the 1988 campaign; for some of the meteorites measurements of natural thermoluminescence (NTL) at 300°C exist from [12].

Meteorite	^{10}Be (dpm/kg)	^{26}Al (dpm/kg)	NTL (krad)
Allan Hills 88011 H3	14.8 ± 0.9	38.3 ± 2.9	
Allan Hills 88020 H3	18.3 ± 1.2	42.8 ± 2.5	210. ± 2.0
Allan Hills 88036 H3	12.0 ± 0.9	42.3 ± 2.5	20. ± 9.0
Allan Hills 88013 H4	15.1 ± 0.9	52.6 ± 3.9	
Allan Hills 88016 H4	19.9 ± 1.2	56.4 ± 4.1	
Allan Hills 88017 H4	20.0 ± 1.2	56.8 ± 4.8	
Allan Hills 88008 H4/5	18.6 ± 1.1	55.6 ± 4.3	
Allan Hills 88010 H4/5	16.6 ± 1.0	42.7 ± 3.1	
Allan Hills 88031 H4/5	17.0 ± 0.9	56.1 ± 3.2	
Allan Hills 88014 H5	15.5 ± 1.0	56.5 ± 4.1	32.0 ± 0.1
Allan Hills 88019 H5	5.6 ± 0.4	10.4 ± 1.2	
Allan Hills 88025 H5	16.1 ± 0.9	52.1 ± 3.2	27.7 ± 0.3
Allan Hills 88026 H5	20.8 ± 1.1	56.2 ± 3.4	127.1 ± 0.5
Allan Hills 88027 H5	19.4 ± 1.1	55.4 ± 3.7	176. ± 1.0
Allan Hills 88028 H5	15.4 ± 1.0	37.0 ± 2.3	0.8 ± 0.1
Allan Hills 88029 H5	18.1 ± 1.1	53.4 ± 4.4	226. ± 2.
Allan Hills 88030 H5	18.5 ± 1.0	48.4 ± 3.1	120. ± 3.
Allan Hills 88032 H5	15.1 ± 0.8	34.7 ± 3.0	60. ± 0.4
Allan Hills 88033 H5	17.0 ± 0.9	62.3 ± 3.4	117.5 ± 0.5
Allan Hills 88038 H5	15.1 ± 1.1	61.5 ± 3.6	27 ± 0.3
Allan Hills 88039 H5	16.6 ± 1.1	58.1 ± 3.5	145.1 ± 0.1
Allan Hills 88040 H5	17.0 ± 0.9	60.8 ± 3.1	32 ± 0.1
Allan Hills 88042 H5	15.7 ± 0.8	58.6 ± 3.1	238.3 ± 0.3
Allan Hills 88018 H6	19.4 ± 1.2	53.1 ± 3.5	
Allan Hills 88021 H6	17.5 ± 0.9	51.9 ± 3.3	
Allan Hills 88043 H6	17.4 ± 0.9	58.6 ± 2.8	
Allan Hills 88002 L4	18.6 ± 1.1	52.1 ± 3.4	
Allan Hills 88012 L6	18.1 ± 1.2	65.3 ± 5.4	
Allan Hills 88024 L6	16.4 ± 0.9	36.5 ± 2.3	9.4 ± 0.1
Allan Hills 88004 LL4	13.2 ± 0.8	73.4 ± 4.5	

accept the other three pairings. A final discussion will be possible when the rare gas data are available.

With the exception of Allan Hills 88019, all ^{26}Al data are in the range observed in H- and L-chondrite falls or of production rates calculated for meteoroids with radii up to 50 cm (Fig. 1), although some of them are probably affected by substantial terrestrial ages. Beryllium-10 data of four meteorites (Allan Hills 88004, Allan Hills 88011, Allan Hills 88019, and Allan Hills 88036) are too low to fit into the range of ^{10}Be activities in normal-sized meteorites (Fig. 1).

However, a mere comparison of individual radionuclide activities with possible production rate ranges is not sufficient. The correlation between production rates of cosmogenic radionuclides must also be taken into account. Such a correlation is shown in Fig. 1, defining a field of allowed ^{10}Be and ^{26}Al concentrations, provided that the activities of these meteorites are in saturation. For meteoroid radii between 5 cm and 40 cm, there is a nearly linear correlation between ^{10}Be and ^{26}Al production rates. For larger radii the linear correlation breaks down as a consequence of ^{10}Be being a medium-energy product and ^{26}Al being a low-energy one. If ^{10}Be and ^{26}Al are in saturation, their correlation can give some evidence of size of the meteoroid and of shielding depth for meteoroid radii above 40 cm. For smaller radii the information on size and shielding becomes more ambiguous.

Comparing the experimental results with the allowed field of ^{10}Be-^{26}Al combinations makes it possible to identify long terrestrial ages, complex exposure histories, and possible contributions of solar cosmic ray interactions. A comparison of the ^{10}Be and ^{26}Al results of the Allan Hills chondrites shows that most results can be interpreted as normal depth and size effects, though some ^{10}Be values are relatively low. The data of Allan Hills 88011 and Allan Hills 88036 could be explained by these meteorite samples coming from large meteoroids. A final discussion of this point, which also has to take into account the possibility of old terrestrial ages, can only be made when the rare gas data are available.

The results for Allan Hills 88004 do not fall into the allowed field of ^{10}Be-^{26}Al data explainable by GCR interactions. This meteorite had a recovered mass of 315.7 g, which gives a lower limit of its preatmospheric radius (2.8 cm). A possible explanation could be that this meteorite comes from a very small (R < 5 cm) meteoroid and that the high ^{26}Al activity is a result of SCR interactions. Also, this question can only be answered when rare gas data are available.

In the case of Allan Hills 88019, the situation is more complicated. Scherer [13] measured He, Ne, and Ar isotopes and derived a mean exposure age of 41.26 Ma based on $T_{exp,3}$ = 33.62 Ma, $T_{exp,21}$ = 42.03 Ma, and $T_{exp,38}$ = 40.48 Ma. He assumed a ^{3}He loss of 18.5% although the gas retention ages are 4.16 b.y. and 3.5 b.y. for ^{40}Ar and ^{4}He respectively. According to the rare gas data, ^{10}Be and ^{26}Al were in saturation at the time of fall if Allan Hills 88019 had a single-stage exposure history. The measured ^{10}Be (5.6 ± 0.4 dpm/kg) and ^{26}Al (10.4 ± 1.2 dpm/kg) data are extremely low and fall significantly outside the allowed field of ^{10}Be/^{26}Al values. These extraordinary results were confirmed by repeated analysis for the same sample and by analysis of a new sample that was analyzed before by Scherer [13] for rare gases. These analyses resulted in 6.0 ± 0.4 dpm/kg, 5.4 ± 0.5 dpm/kg, and 5.4 ± 0.5 dpm/kg for ^{10}Be and 10.3 ± 1.2 dpm/kg and 10.5 ± 1.3 dpm/kg for ^{26}Al. A third ^{26}Al sample awaits AMS measurement. A detailed discussion of the results obtained for Allan Hills 88019 will be performed when this measurement and planned investigations of cosmic ray tracks are finished.

Ordinary Chondrites from the Sahara—Results and Discussion: Thirteen ordinary chondrites from the Sahara were analyzed for ^{10}Be, ^{14}C, and ^{26}Al (Table 3). For three of these meteorites, ^{26}Al has yet to be measured, and rare gas measurements do not yet exist. There are some ^{10}Be and ^{26}Al data that fall outside the systematics. Extremely low ^{10}Be concentrations are found in Hammadah al Hamra 004 and Ilafegh 013. For these two meteorites the ^{26}Al concentrations are also low. The data for Acfer 129 can only be explained as production rates. The high ^{10}Be value of 21 dpm/kg proves that ^{26}Al and ^{14}C are production rates. The ^{26}Al value of 88.7 dpm/kg is exceptionally high, and our only explanation is that we have some ^{26}Al produced by solar cosmic rays in this meteorite.

All ^{14}C concentrations measured in the 13 ordinary chondrites from the Sahara are substantially lower than for falls. A comparison of the measured ^{10}Be activities and the ^{10}Be production rate ranges ensures that ^{14}C was in saturation in all meteorites at the time of fall. In order to analyze these data with respect to terrestrial ages, ^{14}C production rates have to be assumed. According to our model calculations, the ^{14}C GCR production rates in chondrites vary between 18 and 57 dpm/kg in H chondrites (Fig. 2) and between 19 and 60 dpm/kg in L chondrites. Depth- and size-corrected production rates should therefore be used for the determination of terrestrial ages. Such production rates can be obtained by model calculations from

TABLE 3. Analyses of ordinary chondrites from the Sahara cosmogenic radionuclides (^{10}Be, ^{14}C, and ^{26}Al), terrestrial ages, and natural thermoluminescence (NTL) at 300°C.

Meteorite	Class (dpm/kg)	^{10}Be (dpm/kg)	^{26}Al (dpm/kg)	^{14}C (dpm/kg)
Acfer 023	H3	20.4 ± 1.5	61.4 ± 4.7	3.5 ± 0.2
Acfer 129	H3	21.0 ± 1.4	88.7 ± 6.4	4.4 ± 0.2
Acfer 153	H3	15.6 ± 1.3	†	8.5 ± 0.4
Acfer 171	H3.7	18.7 ± 1.3	†	15.2 ± 0.8
Acfer 022	H3.7	17.4 ± 1.1	53.7 ± 4.2	13.5 ± 0.6
Acfer 028	H3.8	20.4 ± 1.5	53.2 ± 4.5	14.7 ± 0.6
Acfer 039	L3	17.6 ± 1.2	46.3 ± 4.1	18.1 ± 0.8
Acfer 066	L(LL)3	17.6 ± 1.2	51.9 ± 5.0	5.9 ± 0.3
Acfer 080	L3.9	14.5 ± 1.1	40.6 ± 3.4	18.0 ± 0.8
Adrar 003	LL(L)3	23.3 ± 1.2	†	19.9 ± 1.0
Ham.Ham.004	H3	13.0 ± 0.9	28.9 ± 2.3	10.5 ± 0.5
Ilafegh 013	H3	9.1 ± 0.7	31.1 ± 2.5	22.2 ± 1.1
Tanezr. 006	H3	16.2 ± 1.1	47.0 ± 3.9	13.2 ± 0.7

Meteorite	Class	P_{14} (dpm/kg)	T_{ter} (k.y.)	$T_{ter,44}$ (k.y.)	NTL (krad)
Acfer 023	H3	47.9	21.6	20.9	3.1 ± 1.2
Acfer 129	H3	56.7*	21.1	19	0.44 ± 0.02
Acfer 153	H3	†	†	13.6	7.2 ± 0.1
Acfer 171	H3.7	†	†	8.8	20.5 ± 5.
Acfer 022	H3.7	42.1	9.4	9.8	0.10 ± 0.01
Acfer 028	H3.8	40.8	8.4	9.1	0.43 ± 0.08
Acfer 039	L3	35.2	5.5	7.3	9. ± 1.
Acfer 066	L(LL)3	39.1	15.6	16.6	12. ± 1.
Acfer 080	L3.9	30.7	4.4	7.4	28. ± 3.
Adrar 003	LL(L)3	†	†	6.6	
Ham.Ham. 004	H3	21.5	5.9	11.8	8. ± 3.
Ilafegh 013	H3	25.2	1	5.7	23. ± 2.
Tanezr. 006	H3	36.5	8.4	10	4. ± 2.

NTL data are from [14]. The ^{14}C-specific activities were derived from the extraction above 1000°C. There are two entries for terrestrial ages: T_{ter} are ages based on depth- and size-corrected ^{14}C production rates (P_{14}); $T_{ter,44}$ denotes terrestrial ages based on an average ^{14}C production rate of 44 dpm/kg.

* The maximum production rate P_{14} was assumed since ^{26}Al is probably affected by SCR-produced ^{26}Al.

† Samples not yet measured.

correlations between ^{14}C production rates and production rates of other radioactive and/or stable cosmogenic nuclides.

In Fig. 2, calculated production rates of ^{14}C, ^{10}Be, and ^{26}Al are presented in the form of a three-isotope plot, plotting $^{14}C/^{10}Be$ vs. $^{26}Al/^{10}Be$. There is a nearly linear correlation between these production rate ratios for meteoroid radii between 5 and 120 cm. Both ratios increase with depth inside a given meteoroid. Furthermore, the ratios in the center of meteoroids increase with radius. The correlation is ambiguous, since the ranges of production rate ratios overlap for different meteoroid radii. But it allows derivation of depth- and size-corrected terrestrial ages if measurements of ^{10}Be, ^{14}C, and ^{26}Al exist for the same sample. One can derive from it the proper production rate of ^{14}C, provided ^{10}Be and ^{26}Al are in saturation. Then we can calculate from the production rates depth- and size-corrected terrestrial ages. This procedure needs a rare gas measurement of the meteorite to assure saturation, but this measurement must not necessarily be a same-sample measurement. If, however, a same-sample measurement of rare gases is available, the proper ^{14}C production rate can also be derived from its correlation with production rate ratios such as $^{22}Ne/^{21}Ne$ or $^{3}He/^{21}Ne$ ratios (Fig. 3).

Though we do not yet have the rare gas measurements, which could assure that ^{10}Be and ^{26}Al are in saturation, the new ^{10}Be, ^{14}C, and ^{26}Al data of the Sahara meteorites were interpreted exemplarily as if ^{26}Al and ^{10}Be were in saturation (Table 3). A comparison of terrestrial ages, based on the shielding-corrected production rates, T_{ter}, and those derived by assuming a mean production rate of 44 dpm/kg, $T_{ter,44}$, clearly demonstrates that shielding corrections should not be neglected for terrestrial age determination. Moreover, the observation of production rates in excess of 44 dpm/kg in stony meteorite falls limits the applicability of the method. The terrestrial ages vary between 1 k.y. and 21.1 k.y. with three meteorites having substantial terrestrial ages of 21.1, 21.6, and 15.6 k.y., while the others are all below 10 k.y.

With the help of these data, some remarks considering pairing can be made. We cannot exclude pairing of Acfer 129 and Acfer 023 having the same terrestrial age. Both have similar ^{10}Be but slightly different ^{26}Al and different ^{14}C. The differences in ^{26}Al could be the result of Acfer 129 coming from the surface and Acfer 023 from the interior of the same meteoroid. This would require that the lower NTL of Acfer 129 is caused by heating of the near-surface parts of the meteoroid. This matter can only be settled after the rare gas data for the other meteorites for which all these radionuclides were measured become available.

Combining the terrestrial ages, ^{10}Be and ^{26}Al, and the NTL data for the other meteorites shows no indication of pairing, and it can be proposed that these meteorites are from different falls. For meteorites from hot deserts with their moderate terrestrial ages, ^{14}C is a good tool to distinguish different falls and to exclude pairing. If we use shielding-corrected terrestrial ages, the time resolution should be sufficient to exclude pairing for these meteorites.

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COMPARISON OF THE DISTRIBUTION OF HALOGENS IN CHONDRITES FROM ANTARCTICA AND FROM WESTERN AUSTRALIA. U. Krähenbühl and M. Langenauer, Laboratorium für Radiochemie, Universität Bern, CH 3000 Bern 9, Switzerland.

All finds of meteorites not sampled immediately after their fall are subjected to alterations, either enrichment due to contamination, or depletion by, e.g., leaching [1]. It is important to know how deeply into the interior such processes affect the original composition of the investigated specimen. After the investigation of the distribution of the four halogens in a large number of H5 and H6 chondrites from different locations within Antarctica, the goal of this investigation was to extend a similar study to samples from a hot desert.

In this study three H5 chondrites from the Nullarbor Plains, Western Australia, with variable terrestrial ages from 1900 to 24,300 yr (^{14}C, [2]) were analyzed for their halogen distribution from the surface into the interior. The results for the chondrites are given in Tables 1–3.

The results show a quite heterogeneous picture. In contrast to samples collected in cold deserts, where a distinct variation with the duration of exposure to the atmosphere can be recognized (this can most easily be seen for F and I), the concentrations of halogens in chondrites from the Nullarbor plains are mainly altered for Cl and Br. No volume concentrations for H5 chondrites of more than 25–50 ppm Cl were found in the Allan Hills. The concentrations of halogens in Reid and Cocklebiddy do not represent original chondrite concentrations. The high contamination in Cl is also reflected in the high Br values. The extremely uniform concentrations of F and I are also evident. Methyliodide is not a major source for contamination of meteorites from the Plains. We recognize that the diffusion into the interior of a specimen is much more important for meteorites collected in hot environments compared to samples originating from Antarctica.

TABLE 1. Halogens in Reid 006.

Depth (mm)	F (ppm)	Cl (ppm)	Br (ppm)	I (ppm)
0.0–0.5	15.8	254	1.09	0.42
0.5–1.0	11.0	181	0.59	0.18
1.0–1.5	7.9	241	0.79	0.25
1.5–2.0	8.0	217	0.88	0.19
2.0–3.0	19.0	593	1.50	0.24
3.0–4.0	10.7	491	1.80	0.29
4.0–5.0	10.9	503	1.40	0.30

TABLE 2. Halogens in Mundrabilla 002.

Depth (mm)	F (ppm)	Cl (ppm)	Br (ppm)	I (ppm)
0.0–0.5	15.5	191	0.93	0.35
1.0–1.5	14.0	195	0.70	0.25
3.0–4.0	19.0	255	0.91	0.33
5.0–6.0	17.0	219	1.00	0.39
6.0–7.5	18.2	262	1.09	0.36

TABLE 3. Halogens in Cocklebiddy.

Depth (mm)	F (ppm)	Cl (ppm)	Br (ppm)	I (ppm)
0.0–0.5	15.3	731	1.9	0.3
2.0–3.0	28.0	1528	2.3	0.25
5.0–6.0	8.4	1095	2.1	0.19

The measured distribution of the four halogens cannot be simply the result of a single operating process. Besides the contamination, a second mechanism, removing some of the elements of interest from outer layers, must have been active. The alteration processes may affect not only the chemical composition but also (for example) determinations of terrestrial ages.

Is it possible that some of the earlier enrichments of halogens were leached later by liquids? Is there other evidence for the presence of liquid water throughout the terrestrial history of the investigated meteorites?

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POPULATIONS, PAIRING, AND RARE METEORITES IN THE U.S. ANTARCTIC METEORITE COLLECTION. M. M. Lindstrom[1] and R. Score[2], [1]Mail Code SN2, NASA Johnson Space Center, Houston TX 77058, USA, [2]Lockheed Engineering and Sciences Corporation, Houston TX 77058, USA.

Introduction: Meteoriticists have long known that the populations of various meteorite types are different for falls and finds [1]. This is attributed to the preferential collection of iron meteorites as finds because they are dense and easier to distinguish from terrestrial rocks. It was hoped that collection of Antarctic meteorites on ice would be less biased and that Antarctic meteorites would be more representative than other meteorite finds. The last few years have seen a major debate about whether Antarctic meteorites represent different populations than meteorite falls [2,3]. We present a review of the populations of meteorites in our collection, pairing of Antarctic meteorites, and the abundances of rare meteorites. We show that our best estimate of Antarctic meteorite populations is very similar to that of falls, except that rare meteorites are more abundant in Antarctic meteorite collections, presumably because they are small and hard to find in other environments.

Populations: The populations of major meteorite types for non-Antarctic falls and finds, and Antarctic finds are given in Table 1. The first three populations are based simply on the total numbers of meteorites. This overall distribution of Antarctic meteorites is more similar to that of non-Antarctic falls than to finds; however, the Antarctic population is enriched in ordinary chondrites and depleted in achondrites, stony irons, and irons relative to that of falls. This comparison is flawed by the uncertainty in the number of individual meteorites that the Antarctic meteorites represent. The Antarctic data do not subtract for the possible pairing of two or more meteorite fragments (see below). To avoid this problem, some investigators [6,7] have chosen to compare mass distributions like those in columns 4 and 5. However, the simple mass distributions

TABLE 1. Populations of meteorite types (percentages of meteorite types are compared for U.S. Antarctic meteorites[4] and non-Antarctic falls and finds [5]).

Meteorite type	Non-Ant. falls #	Non-Ant. finds #	U.S. Ant. finds #	Non-Ant. falls wt.	U.S. Ant. finds wt.	U.S. Ant. # P = 5
Ord. chond.	79.5	49.4	90.2	72.0	77.0	79.5
Carb. chond.	4.2	1.9	3.6	3.1	0.8	5.2
Enst. chond.	1.6	0.7	1.1	nd	0.2	1.7
Achondrite	8.3	1.4	3.4	9.4	2.7	8.5
Stony-iron	1.2	3.6	0.4	4.1	1.6	0.9
Iron	5.1	43.0	1.2	11.2	17.6	4.3
Total met.	830	1588	5702	14,904 kg	1902 kg	1294

listed here are skewed by the inclusion of large Antarctic irons not found on ice as part of the thorough meteorite search [6,8]. Analysis and modeling of the meteorite mass distributions [6,7] concluded that there was no significant difference between falls and Antarctic finds. However, Lipschutz and colleagues [2,9] have argued, based on the numbers of meteorites, that differences in populations are significant. As part of this debate, we offer a simple method of estimating the numbers of Antarctic meteorites that includes pairing corrections for meteorite showers.

Pairing: Meteorites often fall as showers of a few to many fragments. When this happens most places in the world, all fragments are grouped together as the same meteorite. In the Antarctic, meteorites from many different falls are concentrated together [8], and it is not simple to determine which ones are from the same fall, or which are paired specimens. The problem of pairing in Antarctic meteorites has been discussed by several authors [10–12] who have concluded pairing would reduce the number of Antarctic meteorites by factors of 2–10, but most likely 2–6. It is relatively simple to evaluate pairing among the less common meteorite types. Meteorites that are similar to each other and collected in close proximity are most likely from the same fall. Our database of U.S. Antarctic meteorites [4] includes pairing estimates that are known with varying certainty [11]. There are 150 pairing groups among the 5700 classified meteorites, with 2–678 meteorites per group. There are, however, only 16 groups with over 10 meteorites, and of these only 5 groups have over 25 meteorites. Among the less common meteorites, the number of meteorites per group exceeds 10 in only a few cases: the 20 Allan Hills aubrites, 14 Allan Hills eucrites, 34 Allan

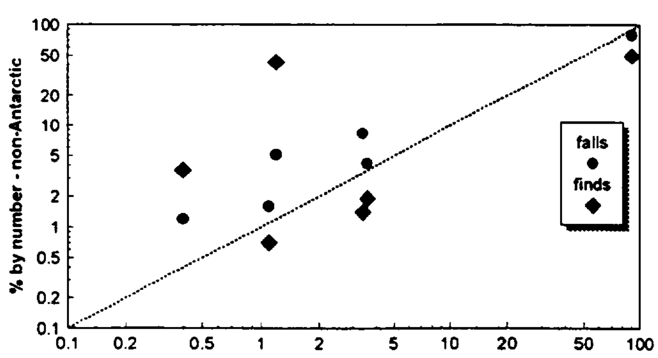

Fig. 1. Meteorite populations by number. This diagram compares populations for falls, finds, and Antarctic meteorites and shows that Antarctic meteorites are more like falls than finds.

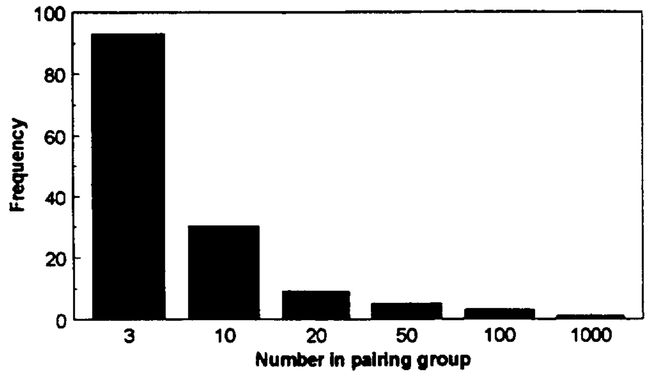

Fig. 2. Pairing of Antarctic meteorites. This histogram of the number of meteorites per pairing group shows that the average number of Antarctic meteorites per pairing group is 5.

Hills CM2, 16 Elephant Moraine CR2, 47 Elephant Moraine CK5 carbonaceous chondrites, and 21 Pecora Escarpment EH3 enstatite chondrites. The average number of specimens per group for the 67 pairing groups of the less-common meteorites is 5, in the range of previous estimates of pairing ratios. It is clear that the number of meteorites in a group increases with the the total mass of the group. Among ordinary chondrites pairing is much less certain, but there are some large pairing groups for the Allan Hills L3, Queen Alexandra Range L5, and Elephant Moraine L6 chondrites. It is much harder to estimate pairing among H compared to L chondrites, and fewer H pairing groups. We do not believe that this is accurate, but instead think that there are unidentified pairings among H chondrites. Huss [7] proposed the existence of a large Allan Hills H5 pairing group based on mass distributions. In the absence of accurate pairing data for ordinary chondrites, we feel that it is best to use the average pairing ratio of 5 from the less common meteorites. When the actual pairing-corrected numbers are used for the five less common meteorite types, and a pairing ratio of 5 is used for ordinary chondrites, the populations of Antarctic meteorites are as shown in the last column of Table 1. This population is remarkably similar to that of non-Antarctic falls as given in the first column. We see no evidence that the overall population of meteorite types has changed over time.

Rare Meteorites: There is, however, strong evidence that the abundance of rare or anomalous meteorites is significantly higher among Antarctic meteorites [3,13–15]. Table 2 lists the Antarctic

TABLE 2. Populations of U.S. Antarctic meteorite subtypes (percentages are based on pairing-corrected numbers of meteorites except for ordinary chondrites, which are uncorrected).

Achondrites	%	Stony irons	%	Irons	%
Aubrites	4.5	Mesosiderites	73	Grouped	70.4
HED	61.8	Pallasites	9	Group-anom.	8.5
Ureilites	18.2	Lodranites	18	Ungrouped	21.1
Primitive/planet	15.5				
Carbonaceous	**%**	**Enstatite Ch.**	**%**	**Ordinary Ch.**	**%**
C2/CM	53.7	EL	36.4	H	49.3
CO3/CV3	16.4	EH	31.8	L	46.6
CK4-6	14.9	E unclassified	27.3	LL	4.0
C anomalous	10.9	E anomalous	4.5	OC anomolous	0.1

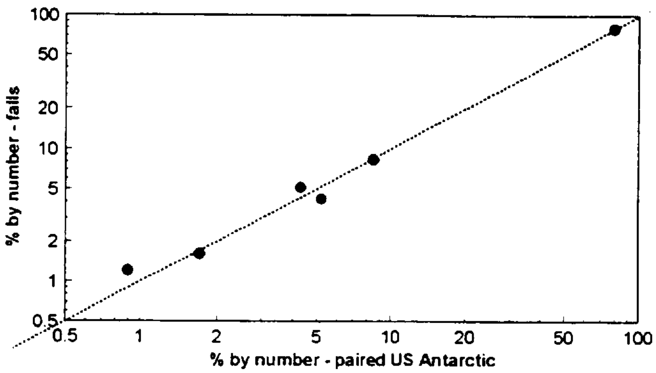

Fig. 3. Meteorite populations by number, pairing corrected. The populations of Antarctic meteorites, when corrected for pairing, is identical to that of falls.

meteorite populations of each of the meteorite subtypes. The last subtype in each major type is that for rare or unusual meteorites. These generally include several different types of meteorites; for example, the achondrites include acapulcoites, angrites, brachinites, lunar meteorites, and martian meteorites. Among non-Antarctic meteorites this subtype would include only a few specimens and would not amount to more than 1–2%. For achondrites, stony irons, irons, and carbonaceous chondrites the abundance of rare meteorites is 10–20%! This surprising abundance of rare meteorites in Antarctica is attributed to the fact that it is easier to find small meteorites on ice than on land. Most rare Antarctic meteorites are small specimens (<30 g). An exception to this is the planetary meteorites. Although lunar meteorites are found almost exclusively in Antarctica, and most lunar meteorites are <30 g, 3 of the 11 are ~500 g. Martian meteorites are generally large. Only one of the four Antarctic meteorites is small, the others being 500 g, 1900 g, and 7900 g. It would appear that a difference in impact dynamics makes these rare planetary meteorites larger specimens.

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THE NOBLE GAS RECORD OF H CHONDRITES AND TERRESTRIAL AGE: NO CORRELATION.

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On the basis of statistically significant concentration differences of some trace elements, it has been suggested that H chondrites found in Antarctica and modern falls represent members of different extraterrestrial populations with different thermal histories [e.g., 1]. It was also concluded that H chondrites found in Victoria Land (Allan Hills) differ chemically from those found in Queen Maud Land (Yamato Mountains), an effect that could be based on the different terrestrial age distribution of the two groups [2]. This would imply a change of the meteoroid flux hitting the Earth on a timescale that is comparable to typical terrestrial ages of Antarctic chondrites.

A comparison of the noble gas record of H chondrites from the Allan Hills ice fields and modern falls [3] shows that the distributions of cosmic ray exposure ages and the concentrations of radiogenic ^{4}He and ^{40}Ar are very similar. In an earlier paper [4] we compared the noble gas measurements of 20 Yamato H chondrites with meteorites from the Allan Hills region and modern falls. Very similar distributions were also found here.

A possible variation of the meteoroid flux with time is perhaps not very obvious because the distribution of terrestrial ages of Allan Hills and Yamato Mountain meteorites show a broad overlap. For 37 finds of these groups, trace-element and noble-gas concentrations as well as terrestrial ages are known. In this paper the distribution of cosmic ray exposure ages and radiogenic ^{4}He and ^{40}Ar contents as a function of terrestrial age are investigated. The cosmic ray exposure ages are derived from the concentration of cosmogenic ^{21}Ne using the production rates and shielding corrections given by Eugster [5]. The lefthand side of Fig. 1 shows the exposure ages of H falls calculated from literature values [6]. Only measurements with cosmogenic $^{22}Ne/^{21}Ne$ between 1.08 and 1.18 were taken into account to reduce uncertainties caused by extreme shielding conditions. The distribution shows the well-known 7-Ma cluster, indicating that about 40% of the H chondrites were excavated from their parent body in a single event. The distribution for all Antarctic H chondrites from [3] and [4] is shown in the middle of Fig. 1. The righthand side of the figure shows the exposure age of Antarctic H chondrites plotted as a function of their terrestrial age. No correlation between exposure age and terrestrial age is observed. Both populations, Antarctic meteorites and falls, exhibit the same characteristic feature: a major meteoroid-producing event about 7 Ma ago. This indicates that one H-group population delivers H chondrites to Antarctica and the rest of the world.

Similar comparisons are made for the radiogenic nuclides ^{4}He and ^{40}Ar. H falls show a maximum between 1250×10^{-8} cm^3 STP/g and 1500×10^{-8} cm^3 STP/g of radiogenic ^{4}He. For Antarctic H chondrites, most samples fall into this region independent of their terrestrial age (Fig. 2). The distribution of the concentration of ^{40}Ar in H falls has a peak with a maximum between 5500×10^{-8} cm^3 STP/g and 6000×10^{-8} cm^3 STP/g. This distribution is also found in Antarctic meteorites (Fig. 3).

We conclude that cosmic ray exposure ages and thermal history indicators, like radiogenic noble gases, show no evidence of a change in the H-chondrite meteoroid population during the last 200,000 yr.

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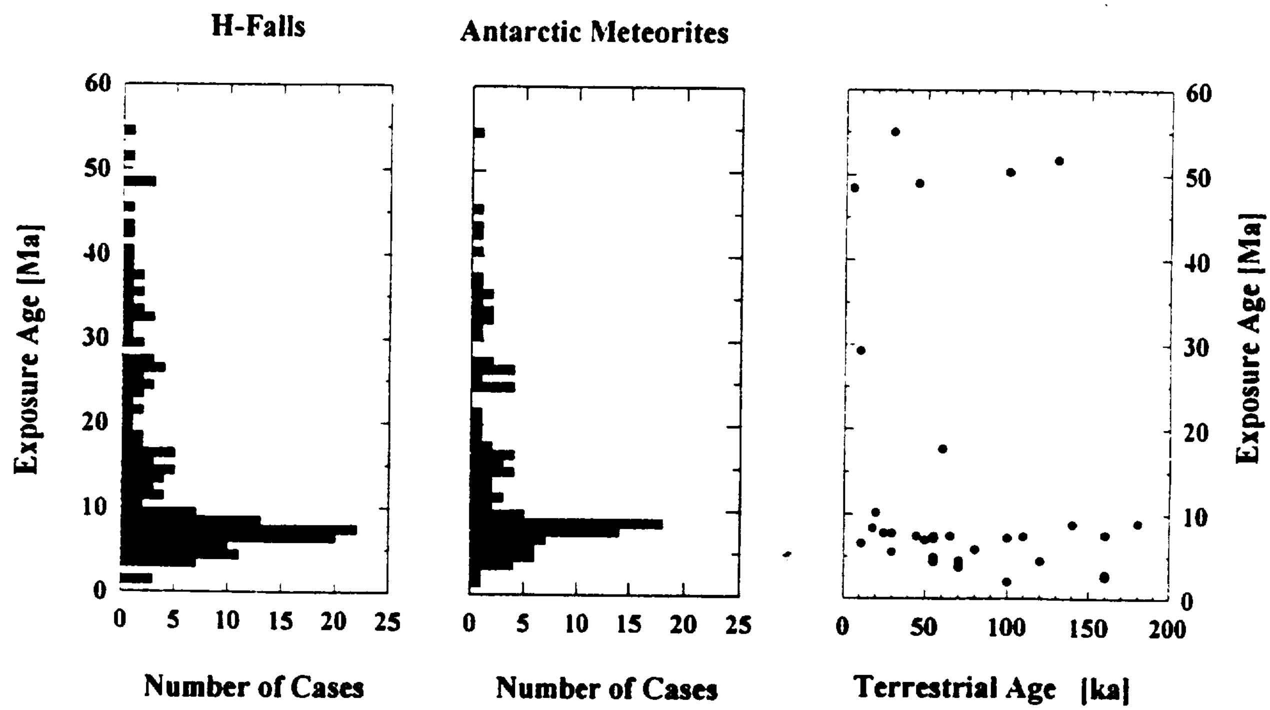

Fig. 1. Exposure age distribution of H chondrites. The histogram of H falls (left) shows the well-known 7-Ma peak, which is also well pronounced for Antarctic H chondrites (middle). No correlation of exposure age and terrestrial age is observed (right).

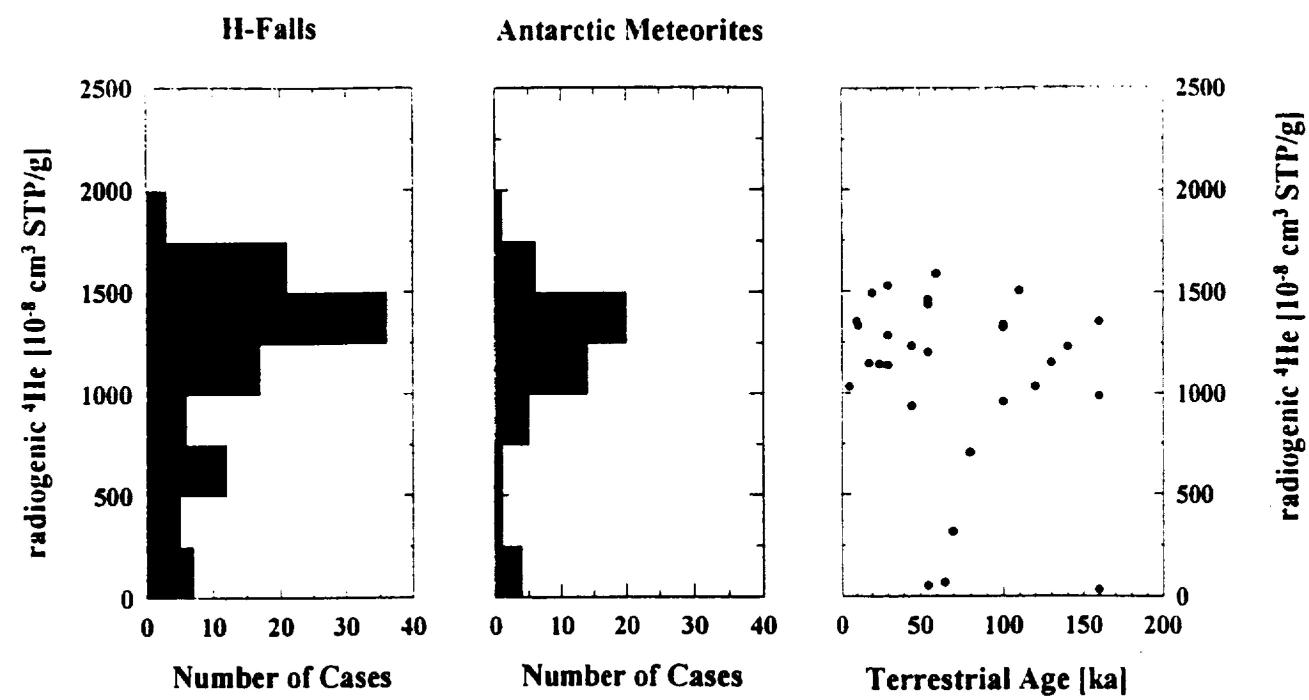

Fig. 2. Contents of radiogenic ^{4}He in H chondrites. The distribution for H chondrites from falls is shown in the left diagram, that for Antarctic meteorites in the middle part. For Antarctic meteorites no dependence on the terrestrial age is observed (right).

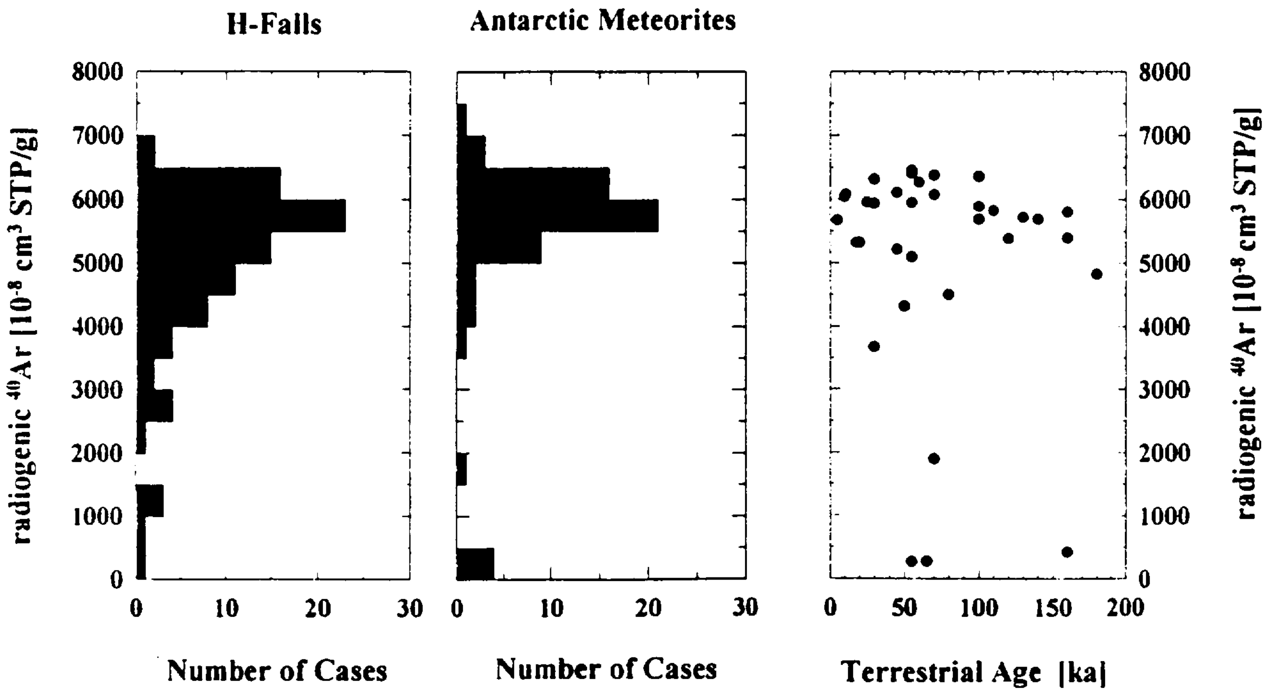

Fig. 3. Distribution of radiogenic ^{40}Ar in H chondrites (left: falls; middle: Antarctic meteorites). No correlation between radiogenic ^{40}Ar and terrestrial age is observed (right).

A HISTORICAL OUTLINE OF METEORITE DISCOVERIES IN AUSTRALIA AND ANTARCTICA. U. B. Marvin, Harvard-Smithsonian Center for Astrophysics, Cambridge MA 02138, USA.

Australia, with its tectonic stability and large areas of arid to semiarid climate with low population density, preserves the most remarkable record of impact features, meteorites, and tektites of any area of similar size in the world. Antarctica, with its vast, shoreward-creeping ice sheet, has yielded the world's most extensive collection of meteorite fragments. These two southern continents exemplify the importance of hot and cold deserts as places to search for evidence of collisions between the Earth and bodies from space. Nevertheless, in both continents the collection and study of meteorites began much later than elsewhere. This paper will briefly outline the history of meteorite and related discoveries in Australia and Antarctica.

Australia: *Tektites.* Archaeological studies show that the aboriginal peoples used australites in their rituals from prehistoric times. The aborigines told the early settlers that these glassy bodies had fallen from the sky. The first description of an australite was written in 1844 by Charles Darwin [1], who had been sent a beautifully flanged specimen collected on a sandy plain between the Darling and Murray Rivers in New South Wales. From its "singular artificial-like" appearance Darwin concluded that it was a volcanic bomb that had burst open and spun rapidly in midair. Knowing that it had been found hundreds of miles from any volcanic region, Darwin commented that it must have been transported either by the aborigines or by natural means. In 1892, Victor Streich sent australites he had collected on the Lindsay expedition through the western deserts to A. W. Stelzner in Germany. Streich thought the tektites were a type of meteorite, but in 1893 Stelzner described them as volcanic in the belief that meteorites contain no glass. Four years later, R. D. M. Verbeek, who had calculated the force of the Krakatau eruption of 1883, proposed that australites and all other tektites known at that time were ejected by volcanos on the Moon. This idea gained widespread support in Australia and Europe [2]. In the early 1960s, after the beginning of the Space Age, interest in tektites soared and new types of chemical and isotopic analyses ultimately led to the current consensus that these bodies are splash glasses from hypervelocity impacts on the Earth's surface. Few investigators dispute this mode of origin, although details of the process remain poorly understood and the elegantly flanged australites, which show clear evidence of two stages of melting, present special problems. In any case, we should note that the Australian aborigines were correct in their belief that the tektites they so prized fell out of the sky.

Meteorites. Unlike tektites, iron meteorites apparently were not put to use by aboriginal peoples anywhere in Australia [3]. The first well-documented discovery of meteorites in Australia occurred as late as 1860, when a supposed deposit of iron found in 1854 near Cranbourne, Victoria, proved to consist of two large, mostly buried, iron meteorites weighing 3.5 and 1.5 tons. (The Baratta stony meteorite may have been discovered in 1845, but documentation is lacking.) Samples of the Cranbourne irons were sent to W. K. von Haidinger in Vienna, who published the first descriptions and analyses of an Australian meteorite in 1861. Twenty-four more meteorites, of which 16 were irons and 1 a pallasite, were found in Australia during the remaining years of the nineteenth century. Thirteen meteorite falls, of which only one is an iron, have occurred in Australia since 1879 (Table 1).

From 1860 to 1955, meteorite discoveries occurred in Australia at an average rate of about one per year [3]. A striking increase in

TABLE 1. Australian meteorite falls [3].

Year	Locality		Class
1879	Tenham	Queensland	L6
1895	Rockhampton	Queensland	Stone
1900	Emmaville	New South Wales	Eu
1902	Mount Browne	New South Wales	H6
1928	Narellan	New South Wales	L6
1930	Moorleah	Tasmania	Iron
1930	Karoonda	South Australia	C5
1942	Forest Vale	New South Wales	H4
1960	Woolgarong	Western Australia	L6
1960	Millibillie	Western Australia	Eu
1967	Wiluna	Western Australia	H5
1969	Murchison	Victoria	CM2
1984	Binningup	Western Australia	H5

discoveries, particularly of stones, followed the dawn of the Space Age in 1957. At first, the increase was due largely to a growth in interest and recognition skills of ranchers, prospectors, and rabbit hunters who work in the outback. More important in recent decades have been systematic searches of desert areas by teams from the Western Australian School of Mines at Kalgoorlie and the Western Australian Museum at Perth. Since 1985 the rate of discovery has risen to nearly nine meteorites per year. By 1992 the total number of cataloged Australian meteorites was 278 and counting. The richest area in Australia, and one of the richest in the world, is the Nullarbor Plain with its semiarid climate and flat, treeless expanses of light-colored limestone where meteorites are well preserved and easily recognized. In 1991, the Nullarbor Plain yielded the first lunar meteorite to be found outside Antarctica.

Impact craters. The first meteorite craters to be recognized in Australia were a group of rimmed depressions near Henbury Station, which lies in the central part of the continent 117 km by camelback from the nearest railroad. Early in 1931 two residents of the Henbury area independently brought these craters to the attention of Professor Kerr Grant at the University of Adelaide. Their interest was sparked by widespread publicity given the fall of the Karoonda meteorite from a spectacular fireball in South Australia on November 25, 1930. Sir Douglas Mawson, then serving as honorary mineralogist at the South Australia Museum, recommended that the reports be investigated. Shortly thereafter, Arthur R. Alderman, of the University of Adelaide, visited the Henbury site and located 12 shallow craters (1 more was found later) in a semiarid plain strewn with iron meteorites. Masses of black glass lay just outside the two largest craters. The Henbury craters proved to be crucial in gaining acceptance for the highly controversial idea of meteorite impact as a crater-forming process. Acrimonious debate still persisted on the impact vs. volcanic origin of "Meteor Crater," 1.3 km across, near Winslow in northern Arizona. The only other feature for which an impact origin had been proposed was the crater, 161 m in diameter, at Odessa, Texas, first described in 1928. Specimens of Henbury meteorites and glass were sent to Leonard J. Spencer at the British Museum, who compared them with those from the craters at Wabar, Arabia, discovered in 1932. In 1933, Spencer [4] published a landmark paper, "Meteorite Craters as Topographic Features of the Earth's Surface," in which he established the authenticity of impact craters as geological phenomena.

TABLE 2. Australian impact structures, 1987 [5].

Year Identified		
1932	Henbury Craters	Northern Territory
1933	Mt. Darwin	Tasmania (confirmed 1973)
1937	Boxhole	Northern Territory
1938	Dalgaranga	Western Australia (noted 1923)
1947	Wolfe Creek	Western Australia
1967	Gosses Bluff	Northern Territory
1970	Strangways	Northern Territory
1971	Liverpool	Northern Territory
1973	Kelly West	Northern Territory
1976	Veevers	Western Australia
1980	Goat Paddock	Western Australia
1980	Teague Ring	Western Australia
1982	Lawn Hill	Queensland
1984	Fiery Creek Dome	Queensland
1986	Lake Acraman	South Australia
1987	Connaly Basin	Western Australia
1987	Mt. Toondina	South Australia
1987	Piccanniny	Western Australia
1987	Spider	Western Australia

Spencer argued that, far from being simple dents or pits in the ground, true impact craters result from the explosive release of energy when hypervelocity meteorites strike the Earth. By 1987 nineteen impact structures had been identified in Australia (Table 2), and searches continue for additional ones [5]. These structures range in size and age from the Dalgaranga Crater, 24 m in diameter and less than 3000 yr old, to the 600-m.y.-old Lake Acraman structure 35 km in diameter. Lake Acraman is one of the most remarkable impact sites in the world. The event projected shocked fragments of a 1600-m.y.-old volcanic complex for distances of 300–450 km where the breccia serves as a 600-m.y.-old horizon marker in late Precambrian sections [6].

Antarctica: *Early meteorite discoveries.* The first meteorite to be discovered in Antarctica was a 1-kg stone lying on compact sastrugi in Adelie Land. It was collected in 1912 by a member of the Australasian Antarctic expedition of 1911–1914 led by the Australian geologist Douglas Mawson [7]. Named "Adelie Land" and classified in recent years as an L5 chondrite, the main mass now resides in the South Australia Museum at Adelaide. Half a century passed before any more meteorites were found in Antarctica. In 1961 members of the Sixth Soviet Antarctic Expedition, mapping a gneiss-diorite formation at an altitude of about 3000 m in the Humboldt Mountains, collected two fragments, weighing 8 and 2 kg, of an iron meteorite. The pieces lay about 7 cm apart on a rock-strewn surface approximately 40 m from the edge of the ice sheet. Both were severely weathered with ridged surfaces displaying Widmanstätten structure. The larger mass was also marked by deep fissures that appeared to have been widened by a long succession of freezing and thawing episodes. This process may well have caused the smaller fragment to spall off the larger. The meteorite was named "Lazarev" for one of the base camps of the Soviet expedition, and pieces eventually were deposited at the Academy of Sciences in Moscow and the municipal museum in Leningrad. In 1975, Vagn F. Buchwald [8] wrote that certain anomalous aspects of the metal indicate that the Lazarev meteorite probably is not an iron but a

TABLE 3. Antarctic meteorite finds.

Chance Discoveries: 1912–1969				
1912	Adelie Land	1	Stone	Austr. Expedition
1961	Lazarev	1	Iron or pallasite	USSR
1962	Thiel Mts.	1	Pallasite	USA
1964	Neptune Mts.	1	Iron	USA
1969	Yamato Ice Fields	9	Stones	Japan
Directed Searches: 1973–1993				
Japan			8,424	
USA			6,391	
EUROMET			285	
N. Zealand			16	
Total Fragments			15,116	
Total Meteorites			~1,500 (?)	

metallic remnant of a pallasite from which the olivine crystals have been lost. Two pieces of an authentic pallasite, weighing 23 and 9 kg, were found lying about 90 m apart on the surface of a glacier by a U.S. team working in the Thiel Mountains in 1962. The main mass of the "Thiel Mountains" pallasite resides in the U.S. National Museum in Washington. In 1964, two engineers in a U.S. field party found an iron meteorite, weighing just over 1 kg, among glacial cobbles about 30 m above the surface of the ice surrounding a nunatak in the Neptune Mountains. The "Neptune Mountains" meteorite retains patches of fusion crust and appears so well preserved that it seems unlikely to have been transported very far by the ice [9]. Perhaps it fell where it lay. Each of these four meteorites was discovered by parties pursuing other interests (Table 3). No scientist predicted that meteorites would be found in Antarctica other than by chance discoveries.

Meteorites on stranding surfaces. The first indication that the moving ice sheet may concentrate meteorites in what amount to "placer deposits" followed from a report presented by Shima and Shima [10] to the Meteoritical Society in 1973. Their analyses showed that nine meteorites collected in 1969 by Japanese glacial geologists from a small (9 × 5 km) area of the Yamato Mountains ice fields were not shower fragments but samples of four different stony meteorites. This unprecedented discovery gave rise to the concept that, under special circumstances, meteorites from diverse falls may be frozen into the ice and exposed on stranding surfaces—expanses of ice temporarily trapped behind mountain barriers and worn down by wind ablation.

During Shima's presentation, Prof. William A. Cassidy of the University of Pittsburgh decided to submit a proposal to the National Science Foundation, which funds all Antarctic research by U.S. scientists, to search for meteorite concentrations within helicopter range of McMurdo Station, across the continent from the Yamato Mountains. On returning home he reported the Shimas' results to Dr. Takesi Nagata, Director of Japan's National Institute of Polar Research, who was visiting the University of Pittsburgh at that time. Nagata sent a field party back to the Yamato Mountains ice fields in December 1973 to conduct the first search specifically aimed at collecting meteorites in Antarctica. The members recovered 12 more specimens that season. It was by no means a straightforward task to field an American team. A lapse of up to 18 months generally is expected between a scientist's submission of a new proposal to the NSF and his or her arrival in Antarctica. However, as a radical departure from traditional Antarctic programs, Cassidy's proposal received mixed reviews and was declined. Many of the geologists, glaciologists, and other scientists who dominated Antarctic research saw meteorites as being of minimal scientific value, and referees with personal knowledge of the frigid Antarctic wastes viewed the idea of focused searches for them as naive. Cassidy submitted a revised proposal in 1975 that was also declined, but he resubmitted it and it was accepted on short notice after he called the NSF with the news that a Japanese team had just returned with 663 specimens. In 1976, Cassidy led the first U.S. meteorite search in Antarctica. That year Nagata also sent a scientist to search for meteorites out of McMurdo Station, and so joint searches were agreed upon with equal sharing of all specimens found. This arrangement continued for three years. With the exception of 1990, when the season's work was canceled due to lack of logistical support, Cassidy led the U.S. teams every year until 1992, when he passed along the leadership role to his co-investigator, Dr. Ralph Harvey.

By 1994, twenty-one years after the Shimas surprised meteoriticists with their report, more than 15,000 meteorite fragments, possibly representing about 1500 individual meteorites, have been collected from the cold Antarctic deserts by parties from Japan, the U.S., and Europe (Table 3). Research samples have been made available to laboratories worldwide. The inventories include 12 lunar meteorites ejected by meteorite impacts on the surface of the Moon, 4 meteorites showing persuasive evidence of an origin on Mars, and several new species of asteroidal materials. Antarctic meteorite programs have given new impetus to planetary research, and Earth scientists, some of whom initially questioned their value, have engaged in collaborative efforts to relate meteorite concentrations to a wide range of problems, including the dynamics of ice motion, the configuration of bedrock beneath the ice, the ages of ice patches within meteorite stranding surfaces, the sources of volcanic dust bands, and indications of climate changes.

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BERYLLIUM-10 AND ALUMINUM-26 CONCENTRATIONS IN CARBONACEOUS CHONDRITES AND OTHER METEORITE TYPES FROM THE SAHARA. B. Meltzow[1], U. Herpers[1], B. Dittrich-Hannen[2], P. W. Kubik[3], and M. Suter[2], [1]Abteilung Nuklearchemie, Universität zu Köln, D-50674 Köln, Germany, [2]Institut für Teilchenphysik, ETH Hönggerberg, CH-8093 Zürich, Switzerland, [3]Paul Scherrer Institut, c/o ETH Hönggerberg, CH-8093 Zürich, Switzerland.

Introduction: Stable and long-lived products of cosmic ray interactions with extraterrestrial matter constitute a unique record of the history of small bodies in the solar system. Measurements of these cosmogenic nuclides in meteorites allow the investigation of collision and exposure histories of the parent bodies. The measurements of ^{10}Be and ^{26}Al provide additional clues to possible pairings.

Experimental: The investigation reported here encompasses 22 samples from the Algerian Sahara and one from Mongolia, kindly placed at our disposal by the Institut für Planetologie, Münster. Beryllium-10 and ^{26}Al concentrations were measured by means of accelerator mass spectrometry (AMS). Samples for this method were prepared using a chemical procedure that has been described in detail previously [1,2]. The masses of the samples prepared for AMS measurements varied from 50 to 250 mg. The AMS measurements were performed at the PSI-ETH AMS facility in Zürich. Descriptions of the AMS technique are given in [3,4].

For ^{10}Be, the standard "S555" with a nominal $^{10}Be/^{9}Be$ ratio of 95.5×10^{-12} was used; for ^{26}Al, the standards used were "Al9" and "AL1092" with a nominal $^{26}Al/^{27}Al$ ratio of 1190×10^{-12} and 134×10^{-12} respectively. The half-lives utilized to convert the measured data of ^{10}Be and ^{26}Al nuclides into activities are 1.51 Ma and 716 k.y. for ^{10}Be and ^{26}Al respectively.

Aluminum-26 was also measured nondestructively by γ–γ-coincidence counting. The technique used has been described in detail elsewhere [5,6]. Samples investigated in this manner had masses from 3 to 37 g. The accuracy of this method is about 5%.

In Fig. 1 the correlation between the ^{26}Al concentrations determined by γ–γ-coincidence counting and AMS is shown. The individual measurements are represented by different symbols; the solid line was obtained by linear regression. The results of both methods agree, except for a few data points, within the range of the errors. Discrepancies between both methods are not necessarily erroneous, but can be explained by the different sizes of the samples used. Due to depth effects, SCR effects, or chemical inhomogeneities, the activity of a cosmogenic nuclide is not uniform within a large sample.

Results and Discussion: The results of the ^{10}Be and ^{26}Al determinations in C chondrites are given in Table 1, and the results of mesosiderites and other classes of Saharan meteorites are given in Table 2. The classification of the meteorites indicated in the tables was done by Bischoff et al. [7]. For some of the meteorites, exposure ages based on ^{21}Ne determinations [8–10] are available. These ages are also included in the tables.

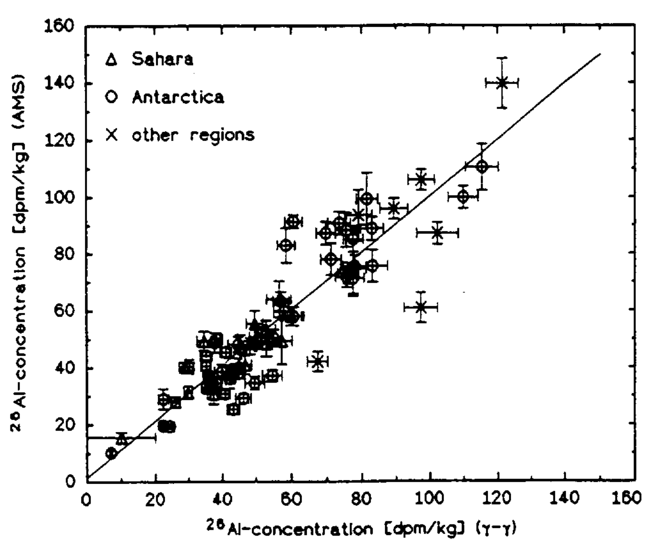

Fig. 1. Comparison of the ^{26}Al concentrations measured by means of AMS and γ-γ-coincidence spectrometry.

TABLE 1. ^{10}Be and ^{26}Al concentrations in C chondrites from the Sahara measured by means of AMS and γ-γ-coincidence spectrometry.

Meteorite	Sample	Class	^{26}Al (dpm/kg) γ–γ	^{26}Al (dpm/kg) AMS
Acfer 094	A 094	CM3	36.8 ± 1.8	33.2 ± 2.1
Acfer 202	A 202	CO3	57.3 ± 2.9	49.4 ± 8.4
Acfer 243	A 243	CO3	28.7 ± 1.7	40.2 ± 1.8
			—	40.2 ± 2.4
Acfer 087	A 87	CR	42.2 ± 1.7	36.9 ± 3.9
Acfer 186	A 186	CR	46.8 ± 1.9	40.9 ± 3.2
El Djouf 001	Dy 1	CR	48.7 ± 2.4	—
Acfer 082	A 82	CV3	26.0 ± 1.3	27.7 ± 1.6
Acfer 086	A 86	CV3	35.5 ± 1.7	32.9 ± 1.6
Acfer 272	A 272	CV3	42.3 ± 2.2	37.7 ± 3.1
Acfer 182	A 182	CH	29.8 ± 1.2	30.8 ± 2.4
Acfer 207		CH	—	29.5 ± 1.5
Meteorite	**Sample**	**Class**	**^{10}Be (dpm/kg) AMS**	**T_{rad} (Ma)**
Acfer 094	A 094	CM3	14.6 ± 0.3	—
Acfer 202	A 202	CO3	3.5 ± 0.8	—
Acfer 243	A 243	CO3	14.4 ± 0.3	—
—	—		15.0 ± 0.3	—
Acfer 087	A 87	CR	17.5 ± 0.7	6
Acfer 186	A 186	CR	21.5 ± 0.3	6
El Djouf 001	Dy 1	CR	19.8 ± 0.7	6
Acfer 082	A 82	CV3	8.5 ± 0.2	—
Acfer 086	A 86	CV3	15.4 ± 0.3	—
Acfer 272	A 272	CV3	13.0 ± 0.3	—
Acfer 182	A 182	CH	16.3 ± 0.6	12.2
Acfer 207	—	CH	16.8 ± 0.5	12.2

The ^{10}Be and ^{26}Al data of the two CO3 chondrites Acfer 202 and Acfer 243 indicate that the two meteorites are not paired. Based on the ^{10}Be and ^{26}Al data presented here, a pairing of the three meteorites Acfer 087, Acfer 186, and El Djouf 001 classified as CR seems very certain. This interpretation of the data is supported by results of mineralogical and petrographical investigations [8]. Remarkable about this pairing is the fact that the El Djouf location is more than 500 km away from the Acfer location. The investigation on 53 H, L, and LL meteorites from the Sahara by Wlotzka et al. [11] indicates that the terrestrial ages of 98% of these meteorites are less than 40,000 yr. Assuming that this is true for C chondrites also, the terrestrial age of the CR chondrites is negligible compared to the half-lives of ^{10}Be and ^{26}Al. The exposure age of 6 Ma implies that the ^{10}Be and ^{26}Al activities are in saturation and consequently represent production rates. In the case of ^{26}Al, this is consistent with the activity range reported for other carbonaceous chondrites [12–14].

Based on the ^{10}Be and ^{26}Al concentrations, a pairing in the case of the CV3 chondrites seems very improbable; this conclusion is supported by mineralogical and petrographical investigations [7]. The ^{10}Be and ^{26}Al concentrations of the two meteorites Acfer 182 and Acfer 207 classified as CH indicate a pairing, and the results of

TABLE 2. ^{10}Be and ^{26}Al concentrations in mesosiderites and other classes from the Sahara* measured by means of AMS and γ–γ-coincidence spectrometry.

Meteorite	Sample	Class	^{26}Al (dpm/kg) γ–γ	^{26}Al (dpm/kg) AMS
Acfer 063	A 063	Meso	37.4 ± 1.9	30.7 ± 3.6
	Silicate	—	—	67.0 ± 3.4
Acfer 265	A 265	Meso	30.7 ± 2.1	—
Ilafegh 002	Il 2	Meso	33.9 ± 1.9	—
	Silicate	—	—	—
Acfer 217	A 217	R	56.5 ± 3.4	64.1 ± 6.4
Acfer 277	A 277	Ure	<10	15.5 ± 1.7
Ilafegh 009	Il 009	EL7/6	68.6 ± 3.4	
Tanezrouft 031	T 31	E	34.5 ± 2.1	49.4 ± 3.3
Acfer 193	—	LL4/6	55.7 ± 2.8	—
Acfer 160	—	LL Brec.	45.4 ± 2.3	—
Adzhi-Bogdo	—	LL3/6 Brec.	56.4 ± 2.8	—
Acfer 031	—	H5	50.0 ± 2.5	—
Acfer 038	—	H5	52.9 ± 4.2	—

Meteorite	Sample	Class	^{10}Be (dpm/kg) AMS	T_{rad} (Ma)
Acfer 063	A 063	Meso	7.0 ± 0.2	—
	—	—	7.3 ± 0.2	—
	Silicate	—	12.1 ± 0.2	—
Acfer 265	A 265	Meso	—	—
Ilafegh 002	Il 2	Meso	4.4 ± 0.2	—
	Silicate	—	8.0 ± 0.3	—
Acfer 217	A 217	R	22.9 ± 0.3	35
Acfer 277	A 277	Ure	2.6 ± 0.8	
	—	—	2.6 ± 0.5	—
Ilafegh 009	Il 009	EL7/6	18.2 ± 0.3	—
	—	—	18.7 ± 0.4	—
	—	—	17.3 ± 0.7	—
Tanezrouft 031	T 31	E	13.0 ± 0.5	—
Acfer 193	—	LL4/6	—	—
Acfer 160	—	LL Brec.	—	—
Adzhi-Bogdo	—	LL3/6 Brec.	18.1 ± 0.5	—
Acfer 031	—	H5	—	—
Acfer 038	—	H5	—	—

*Except for Adzhi Bogdo, which originated in Mongolia.

mineralogical and petrographical investigations [9] support this conclusion. If the terrestrial age of these meteorites is negligible in this case as well, because of the high exposure age of 12.2 m.y., the ^{10}Be and ^{26}Al activities appear to be saturated.

The ^{10}Be data of the two mesosiderites Acfer 063 and Ilafegh 002 (Table 2) and the ^{10}Be concentrations in the stone phases of both meteorites indicate that they are not paired. On the basis of the ^{26}Al data a pairing of Acfer 063 and Acfer 265 seems probable, but the ^{10}Be data are needed to make a more definite conclusion. In the case of Acfer 063 and Ilafegh 002, a magnetic separation of the iron phase from the stone phase was done to investigate the ^{10}Be and ^{26}Al concentrations in the stone phase separately. Taking the saturation activities of eucrites as references (21.8 ± 0.7 and 93 ± 14 dpm/kg respectively [14]), the ^{10}Be and ^{26}Al concentrations in the stone phase of Acfer 063 appear to be undersaturated. Assuming these average saturation activities, the ^{10}Be and ^{26}Al concentrations imply an exposure age of 1–2 Ma.

Acfer 217, classified as a member of the Rumuruti-type chondrite group (R), is another interesting sample that will be discussed here. Based on model calculations the following conclusions about Acfer 217 can be made: The concentrations of all cosmogenic nuclides can be consistently interpreted only if the preatmospheric radius is between 15 and 65 cm, and a single-stage exposure history and low terrestrial age compared to the half-life of ^{26}Al are assumed [10].

The average ^{26}Al and ^{10}Be production rates in ureilites are 42.3 ± 2.2 and 20.3 ± 1.0 respectively [15]. Taking these production rates as references, the low ^{26}Al concentration of 10–15 dpm/kg in Acfer 277 indicates an exposure age of 0.3–0.5 Ma, and the ^{10}Be concentration of 2.6 dpm/kg consistently indicates an exposure age of 0.3 Ma. The ^{26}Al concentrations of the H and LL chondrites as well as the ^{10}Be concentration of Adzhi-Bogdo are within the normal range for these classes [15].

Acknowledgments: We thank the Deutsche Forschungsgemeinschaft for the support of this research.

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CONTAMINATION DIFFERENCES BETWEEN CO3 FALLS AND ANTARCTIC AND SAHARAN FINDS: A CARBON AND NITROGEN ISOTOPE STUDY.

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The C and N isotope characteristics of 16 powdered whole-rock CO3 and related carbonaceous chondrites have been determined using the technique of stepped combustion. The reason for such a study is threefold: (1) as a preview of presolar inventories before more detailed acid residue work, (2) to identify unusual or even unique specimens, and (3) to evaluate contamination differences caused by terrestrial weathering.

Table 1 shows the list of samples, which have been divided into two subgroups: the "normal" CO chondrites, which tend to fall into petrographic subtypes 3.2–3.6 based on olivine compositions [1], and the primitive CM-CO chondrites, which are petrographic subtypes 3.0–3.1. The term CM-CO is used to indicate the similarity between the C and N inventories of these chondrites and members of the CM2 group and particularly the presence in these specimens of presolar silicon carbide; no generic relationship is implied. Acfer 094 possesses mineralogical and chemical characteristics of both groups. It has been described as the first CM3 [2], although on the basis of presolar grain investigations this classification is doubtful [3]. It is better at this stage to refer to it as a unique carbonaceous

TABLE 1. Sample list with collection details of each specimen, petrographic type [1], and subgroups.

Meteorite	Fall/find	Location	Pet. type	Group
Acfer 094	Find	Algeria	3.0	Unique
Allan Hills 77307	Find	Antarctica	3.1	Unique
Colony	Find	Oklahoma	3.0	"CM-CO"
Yamato 81020	Find	Antarctica	3.3	"CM-CO"
Acfer 202	Find	Algeria	3.5	"CM-CO"
Acfer 243	Find	Algeria	3.7	"CM-CO"
Allan Hills 82101	Find	Antarctica	3.4	"CM-CO"
Allan Hills 77003	Find	Antarctica	3.4	"CM-CO"
Felix	Fall	Alabama	3.4	"CM-CO"
Kainsaz	Fall	Russia	3.2	"normal" CO
Lancé	Fall	France	3.4	"normal" CO
Ornans	Fall	France	3.4	"normal" CO
Warrenton	Fall	Missouri	3.6	"normal" CO
Yamato 791717	Find	Antarctica	3.3	"normal" CO
Yamato 82050	Find	Antarctica	3.3	"normal" CO
Yamato 82094	Find	Antarctica	3.5	"normal" CO

chondrite. We have shown that there is little correlation between C and N content with petrographic subtype [4], although the CM-COs contain more C and N than the normal COs. Acfer 094 has the highest bulk C and N content of the group.

In Table 1 it is apparent that the sample list is a variety of falls and finds that were collected from both cold and hot desert environments. There exists, therefore, an opportunity to study the effects of weathering on C and N content and isotopic composition.

Low-temperature C released from Antarctic ordinary chondrites is isotopically heavier than non-Antarctic falls ([5] and Fig. 1). We hoped to see a similar situation in the low-temperature C in the CO chondrites. All the meteorites studied here release some C below 200°C, and the main discussion will be restricted to this material. Nitrogen released at the same temperature is complicated by the presence of heavy N in the organic matter of the primitive specimens. Although generally the finds contain more N at 200°C, there are no isotopic differences between the falls and finds. Similarly, low-temperature H is more abundant in CO3 finds [6], but it is isotopically indistinguishable from that in the falls.

In contrast, the isotopic composition of low-temperature C is related to the circumstances of collection. From Fig. 2 it is evident that low-temperature C in the Antarctic finds is isotopically heavier (i.e., enriched in ^{13}C) than the falls, as is the case in ordinary chondrites. Moreover, there are other isotopic differences within

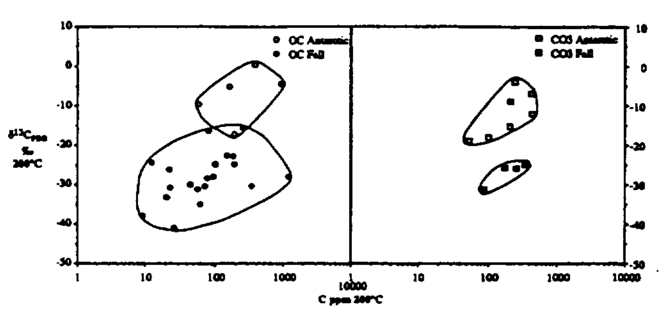

Fig. 1. $\delta^{13}C$ of the 200°C carbon step in ordinary chondrite [5] and CO3 chondrite falls and Antarctic finds.

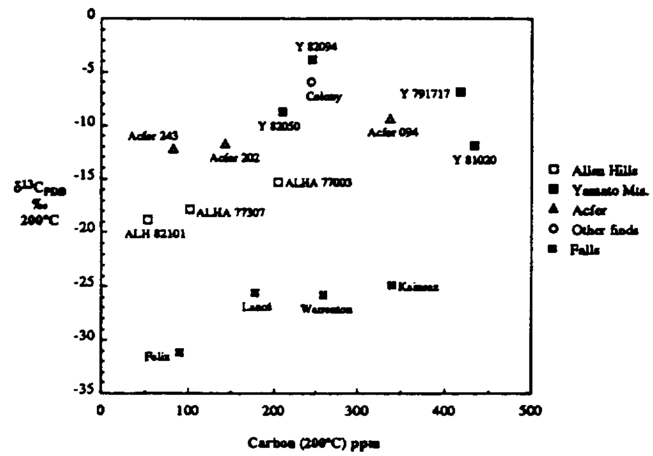

Fig. 2. $\delta^{13}C$ of the C released below 200°C in the CO chondrites.

the sample set. First, the Yamato Mountains samples are both isotopically heavier and contain more 200°C carbon than the Allan Hills samples. In contrast, low-temperature heavy C has not been observed in Yamato ordinary chondrites [7]. The Saharan samples generally contain heavier C than the Allan Hills samples but not quite as heavy as the Yamato Mountains samples.

On the basis of Fig. 2 we can argue that the <200°C combustion fraction for samples collected from different environments may be an indicator of the local contamination potential. The nature of this C has not been positively identified, but possible sources will be discussed here. All these samples lose the low-temperature heavy C when treated with HF/HCl as part of the process of preparing acid-resistant residues. Although this observation is consistent with CO_2-induced weathering, the combustion temperature rules out mineralogically discrete carbonate. Possible sources of C contamination in Antarctica will be discussed first.

Carbon dioxide from air has a $\delta^{13}C$ of about –7‰ and its adsorption onto the Antarctic samples could explain the isotopic composition of most of them. Trapped CO_2 in the ice would have a similar composition. One would expect that air adsorption is uniformly active throughout the entire Antarctic meteorite population. However, whereas CO3 falls and Antarctic finds are easily distinguishable in terms of low-temperature C, the Antarctic and non-Antarctic ordinary chondrites show an overlap in composition (Fig. 1), and this overlap is even more pronounced in the achondrites [5]. This behavior could be caused by the different porosities of these meteorite types, which decrease in the order CO3, OC, achondrites. Porosity will affect all types of contamination.

Antarctic carbonaceous chondrites are particularly susceptible to surficial evaporite formation, which can form over a relatively short period of time [8]. Bicarbonates such as nesquehonite and hydromagnesite have been analyzed in ordinary chondrites, and have been shown to be isotopically heavy (e.g., $\delta^{13}C$ of 7.9‰, Lewis Cliff 85320 nesquehonite [9]). However, it has been tentatively suggested that evaporites forming on carbonaceous chondrites tend to be magnesium sulphates rather than bicarbonates [10]. In addition, bicarbonates combust at higher temperatures—300°–400°C. However, there exists the possibility that the sulphates could contain small amounts of C.

Most biogenic material tends to be isotopically light—25–20‰—and therefore cannot be the cause of heavy C, although it could affect the falls, which have experienced many decades of museum storage. Methyl iodide produced biogenically in the sea and transported by wind could be involved, as it is established that the Antarctic meteorites are overabundant in I [11,12]. However, on the basis of the I abundance it is difficult to attribute enough C to such a source unless the carbonaceous portion of CH_3I is accumulated at the expense of the halide following disproportionation. In the hope of recognizing any terrestrial organic constituents, a sample of Allan Hills 77003 was subjected to online pyrolysis GCMS. A dry-pelleted whole-rock sample was analyzed using a pyrojector (SGE Ltd.) at 500°C; GCMS conditions were the same as [13]. Figure 3 shows the resulting pyrogram. There is no evidence of halogenated compounds that could be equated with sea spray, nor are there any other compounds diagnostic of terrestrial contamination such as isoprenoidal alkanes. Much of the organic matter in Allan Hills 77003 would appear to be PAHs cleaved from the macromolecule.

The $\delta^{13}C$ difference between the two Antarctic collection sites is interesting. One might assume that the nature of the contaminant is the same in both cases, and that the Yamato Mountains samples are simply more weathered than the Allan Hills samples as they contain more low-temperature heavy C. However, if this were the case one would expect the Allan Hills samples to contain the most contamination, as these generally give much older terrestrial ages than the Yamato specimens [14]. Clearly the amount of C contamination is not related to terrestrial age. The possible sources of contamination listed above all occur when the meteorites are exposed to air rather than when buried, so a correlation with exposure of the ice surface would be more likely. It is possible that C contaminants are controlled by physical geography. In this respect it may be significant that the two collection sites lie on opposite sides of the Antarctic continent. Also, the Yamato collection site is nearer to the sea and more exposed than the Allan Hills site. An alternative suggestion is that the difference between the sites is due to different curatorial conditions, as it is well established that discrete generations of salts can grow during storage [9].

The Saharan samples are even more difficult to explain than the Antarctic ones. They could be affected by adsorbed air, biogenic contamination, and evaporite formation, but the composition might also be controlled by water passing through the limestone on which they were collected. Terrestrial calcite that has precipitated from dissolved limestone analyzed in Algerian meteorites has a $\delta^{13}C$ of 10.0‰ [15].

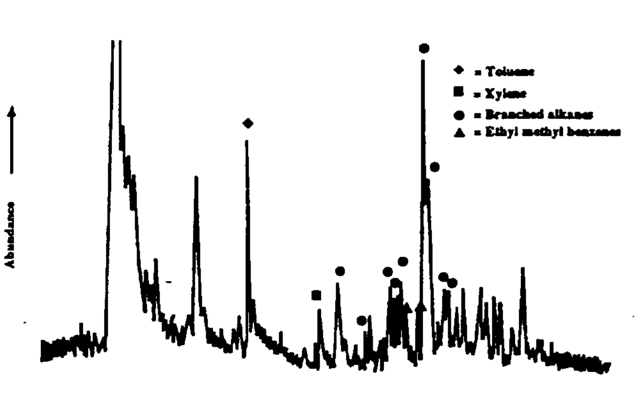

Fig. 3. Allan Hills 77003 pyrogram.

The stepped combustion data suggest the presence of some collection-site-specific form of contamination or weathering. The understanding of the contribution from various sources is likely to require an in-depth study involving other methods of analysis.

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TERRESTRIAL AGES OF METEORITES FROM COLD AND COLD REGIONS.

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We are continuing our ongoing study of cosmogenic nuclides in Antarctic meteorites. The major objective is the determination of the terrestrial ages of meteorites based on ^{36}Cl concentrations. The distribution of meteorite terrestrial ages is one of the most vital pieces of information for studies of ice movement and meteorite accumulation mechanisms in the blue ice areas. In addition to work on terrestrial ages, we are also studying the histories of Antarctic meteorites and cosmic rays. We have measured ^{36}Cl in over 150 Antarctic meteorites since our previous publication [1]. Although much of the new data is still preliminary, some interesting points are already evident. We present here findings and new observations based on both our new results and on previous studies.

Since a large number of meteorites have been recovered from many different ice fields in Antarctica, we continue to survey the trends of terrestrial ages for different ice fields. We have also measured detailed terrestrial ages vs. sample locations for Allan Hills, Elephant Moraine, and Lewis Cliff Ice Fields where meteorites have been found with very long ages. Figures 1a and 1b show the updated histogram of terrestrial ages of meteorites from the Allan Hills Main Ice Field, Allan Hills Far Western and Middle Western Ice Field, Yamato Mountains, Elephant Moraine, Lewis Cliff, and other regions in Antarctica. The figure includes ^{14}C and ^{81}Kr terrestrial ages obtained by other groups. Pairs of meteorites are shown as one object plotted at the average. The width of the bars represents 70,000 yr, which is a typical uncertainty for ^{36}Cl ages. The total amount of data has more than doubled since our previous publication [1].

The Allan Hills Ice Fields and the Allan Hills meteorites are the most intensively and widely studied to date. We have therefore concentrated our studies in this area. Figure 1a clearly indicates that meteorites found at the Allan Hills Ice Fields are much older than any other meteorites. Figure 1a also shows a comparison of the terrestrial ages at both the Allan Hills Main Ice Field and with the

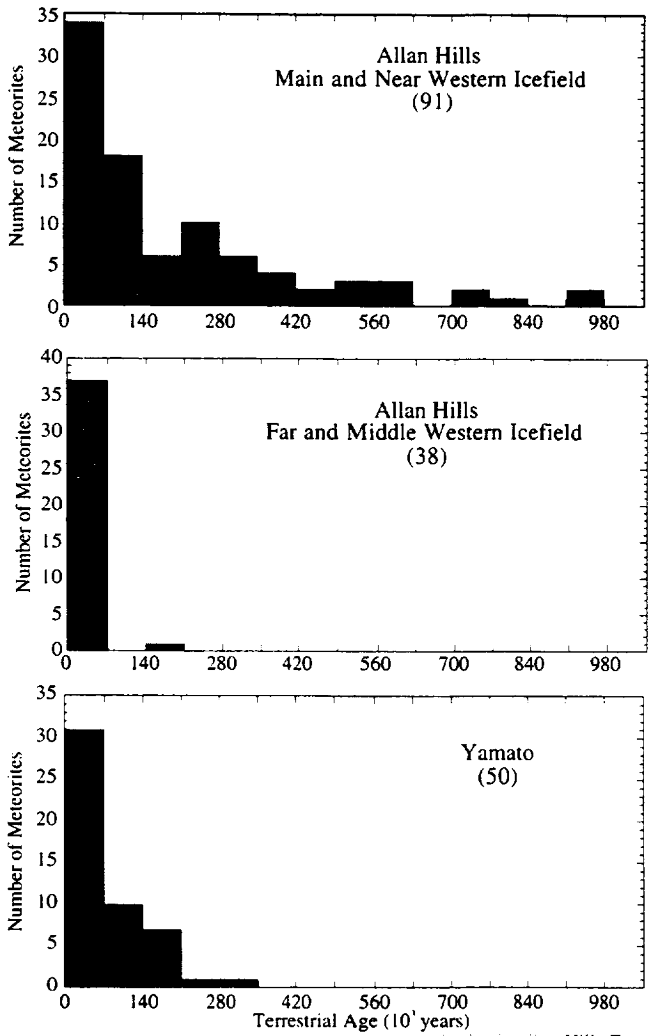

Fig. 1. (a) A histogram of terrestrial ages of Allan Hills Main Ice Field, Allan Hills Far and Middle Western Ice Fields, and Yamato meteorites. The width of the bars represents 70,000 yr.

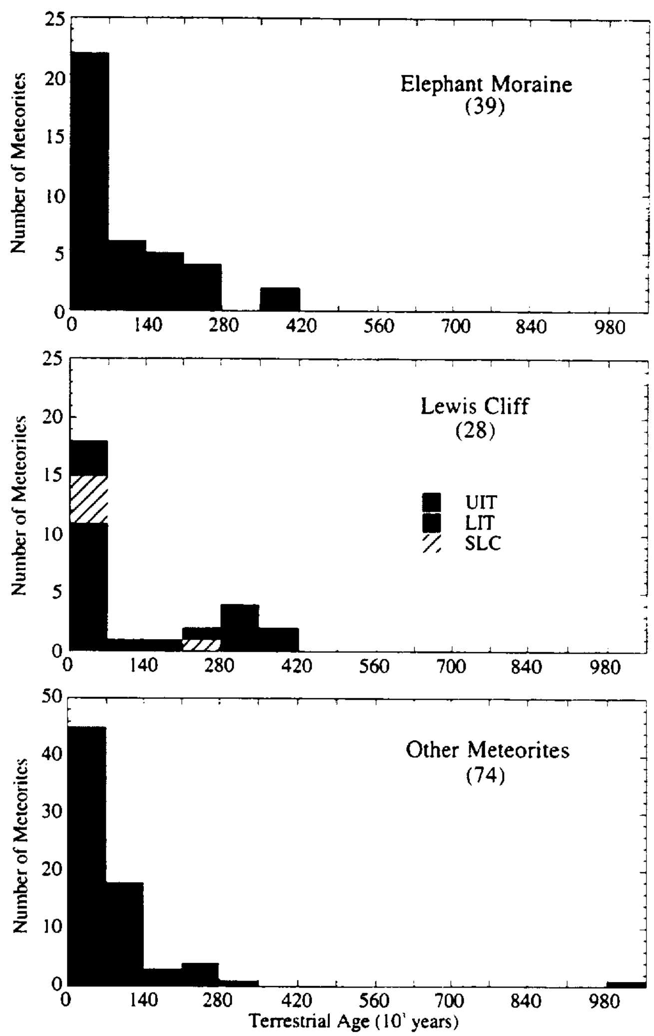

Fig. 1. (b) A histogram of terrestrial ages of Elephant Moraine, Lewis Cliff, and other Antarctic meteorites. The width of the bars represents 70,000 yr.

subsidiary surrounding ice fields. Very old meteorites are only found on the Allan Hills Main Ice Field. The terrestrial ages cover a wide range and are as old as 1 m.y. Delisle and Sievers [2] have performed detailed field studies of ice topography and bedrock topography in the vicinities of the Allan Hills Main Ice Field and the Near Western Ice Field. Many of the old-terrestrial-age meteorites were found over ice with shallow depths (over mesalike bedrock topography). Four Allan Hills meteorites (ALH 84243, 85037, 85048, and 85123) were collected on soil or on bedrock. Three of these have terrestrial ages less than 100,000 yr, but one (ALH 85048) has a 920,000-yr terrestrial age. We do not yet understand the relationship between the terrestrial ages and the histories of the outcrops on which the meteorites were found. It is very important to study the exposure age of the bedrock using *in-situ*-produced cosmogenic nuclides [3].

Many of the Lewis Cliff meteorites are as old as the Allan Hills (Main Ice Field) meteorites. Eight out of 28 Lewis Cliff meteorites have terrestrial ages greater than 200,000 yr. So far, no clear correlation has been found between the terrestrial ages and the locations of the Lewis Cliff meteorites. Old and young meteorites were found on both the Lower and Upper Ice Tongue (see Fig. 1b). The terrestrial age determination of Lewis Cliff meteorites is related to two other projects. We have measured *in-situ*-produced ^{10}Be and ^{26}Al in a series of rocks between the Lewis Cliff Ice Tongue and Law Glacier in collaboration with Dr. G. Faure to investigate the progressive thinning of the East Antarctic ice sheet. The other project is measurement of ^{10}Be, ^{26}Al, and ^{36}Cl in two "horizontal ice cores" that were collected by ANSMET during meteorite search at Lewis Cliff Ice Tongue. We will study the ice cores in collaboration with glaciologists to understand the ice flow at the Lewis Cliff Ice Field and to investigate meteorite accumulation mechanisms.

Although there is no clear correlation between the terrestrial age and weathering category [1], we compare the abundance of metal in chondrites and terrestrial ages of these objects. The abundance of metal yields direct information of chemical weathering in Antarctica. Figure 2 shows the comparison of clean metal abundance in Antarctic H chondrites at different ice fields and non-Antarctic H. Abundance of clean metal in Antarctic meteorites is significantly lower than non-Antarctic.

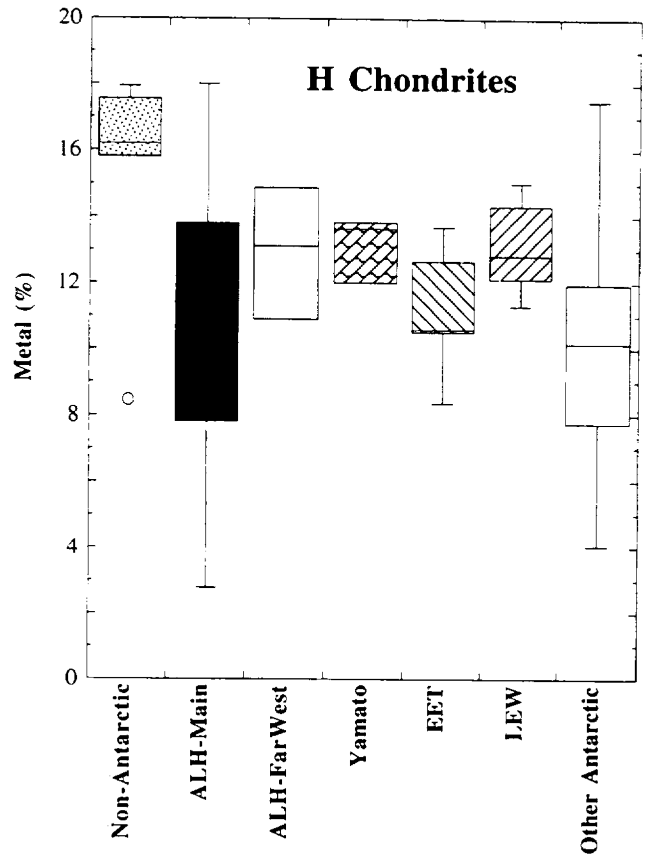

Fig. 2. Comparison of clean metal abundance in Antarctic H chondrites at different ice fields and non-Antarctic H.

Although the precision of ^{36}Cl measurement is now 1–3%, the limitation of ^{36}Cl terrestrial ages is the longer half-life, 300,000 yr, and the range of saturation values. We measured the ^{36}Cl saturation values in 26 chondrites with known terrestrial ages. Previously we used the saturation value 22.8 ± 3.1 dpm [1]. In this study, we found a new saturation value 22.1 ± 1.4 dpm (1σ). This is in good agreement with the previous value but a smaller error.

Acknowledgments: I wish to thank A. J. T. Jull for providing unpublished ^{14}C results. The ^{36}Cl measurements were performed at the University of Rochester and Lawrence Livermore National Laboratory. This work was supported by NASA and NSF grants.

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PRODUCTION PROFILES OF NUCLIDES BY GALACTIC-COSMIC-RAY PARTICLES IN SMALL METEOROIDS.

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Many of the meteorites found in cold and hot deserts are small, and many were small bodies in space. Production of cosmic-ray-produced (cosmogenic) nuclides in small meteoroids is expected to be different than that in the larger meteoroids typically studied [1], with lower levels of nuclide production by galactic-cosmic-ray (GCR) particles [e.g., 2] and possibly significant production by solar-cosmic-ray (SCR) protons [3]. Motivated by the cosmogenic-nuclide measurements for the very small Salem meteorite [4,5] and for cosmic spherules [e.g., 6], which show high levels of SCR production, we have previously reported nuclide production rates by SCR protons in small objects in space [e.g., 3,7]. The GCR production rates reported in [2] for small meteoroids have not been tested and were expected to be poor for meteoroids with radii <40 g/cm^2 because of the very simple nature of that semiempirical model (only one free parameter) and because the mix of neutrons and protons is different (relatively more protons) than that in the model, which was based on larger objects. Thus we have calculated production rates for nuclides made by GCR particles in small objects with a physical model that is much better suited for unusual targets.

The production rates for GCR nuclides were calculated using particle fluxes from the Los Alamos Monte Carlo LAHET Code System (LCS) and measured or evaluated cross sections [8]. LCS has yielded calculated production rates that almost always are in very good agreement with cosmogenic-nuclide measurements in meteorites with radii greater than about 15 cm [8–10]. The fluxes of protons and neutrons in spherical meteoroids of radii 1–45 cm and with an L-chondrite composition were calculated as a function of preatmospheric depth. Production rates for most stony objects are similar to those for L chondrites [8]. The neutron and proton fluxes calculated by LCS were normalized to an effective incident omni-directional GCR proton flux of 4.8 protons/(cm^2 s) [9]. This flux is ~60% higher than that for the primary protons in the GCR as it includes production by alpha particles and heavier GCR nuclei, both directly and by secondary nucleons contributed by the break-up or reactions of these heavier GCR nuclei. We have found that the GCR flux averaged over the orbits of meteoroids are ~5% greater than that at the Moon [11]. For each layer, these fluxes were then multiplied by the neutron and proton cross sections for major target elements and integrated over energy to get the production rates for eight nuclides: ^{10}Be, ^{14}C, ^{21}Ne, ^{22}Ne, ^{26}Al, ^{36}Cl, ^{36}Ar, and ^{53}Mn.

The calculated GCR production rates for the smallest meteoroids are ~70% greater than those calculated using only primary GCR protons by [12], mainly because of the ~60% factor for heavier GCR nuclei, which do not break up or react in very small meteoroids. Our calculated GCR production rates for radii up to ~10 cm also could be high. The only test of GCR production rates in very small meteoroids is the ^{10}Be activities in Salem, which are ≈17 dpm/kg [5], in good agreement with our ^{10}Be production rates calculated for a 3-cm-radius meteoroid. Thus the most serious errors in our calculated production rates are for radii less than ~3 cm.

The plots in Fig. 1 show the results of our production-rate calculations. All the cosmogenic nuclides have GCR production profiles that increase from the preatmospheric surface to a maximum near the center of the meteoroid. The results are basically similar to those in [2]. The amount of this increase varies considerably, with products made by higher-energy particles and by protons, such as ^{10}Be, having less increase in production rate with depth. In all cases, the GCR-calculated production rates in meteoroids with radii less than ~15 cm are much less than those for larger meteoroids. As most cosmogenic-nuclide production rates have been inferred from measured concentrations in such larger meteoroids, their use for small meteoroids results in overestimated production rates. For example, our calculated ^{21}Ne production rate for Salem as

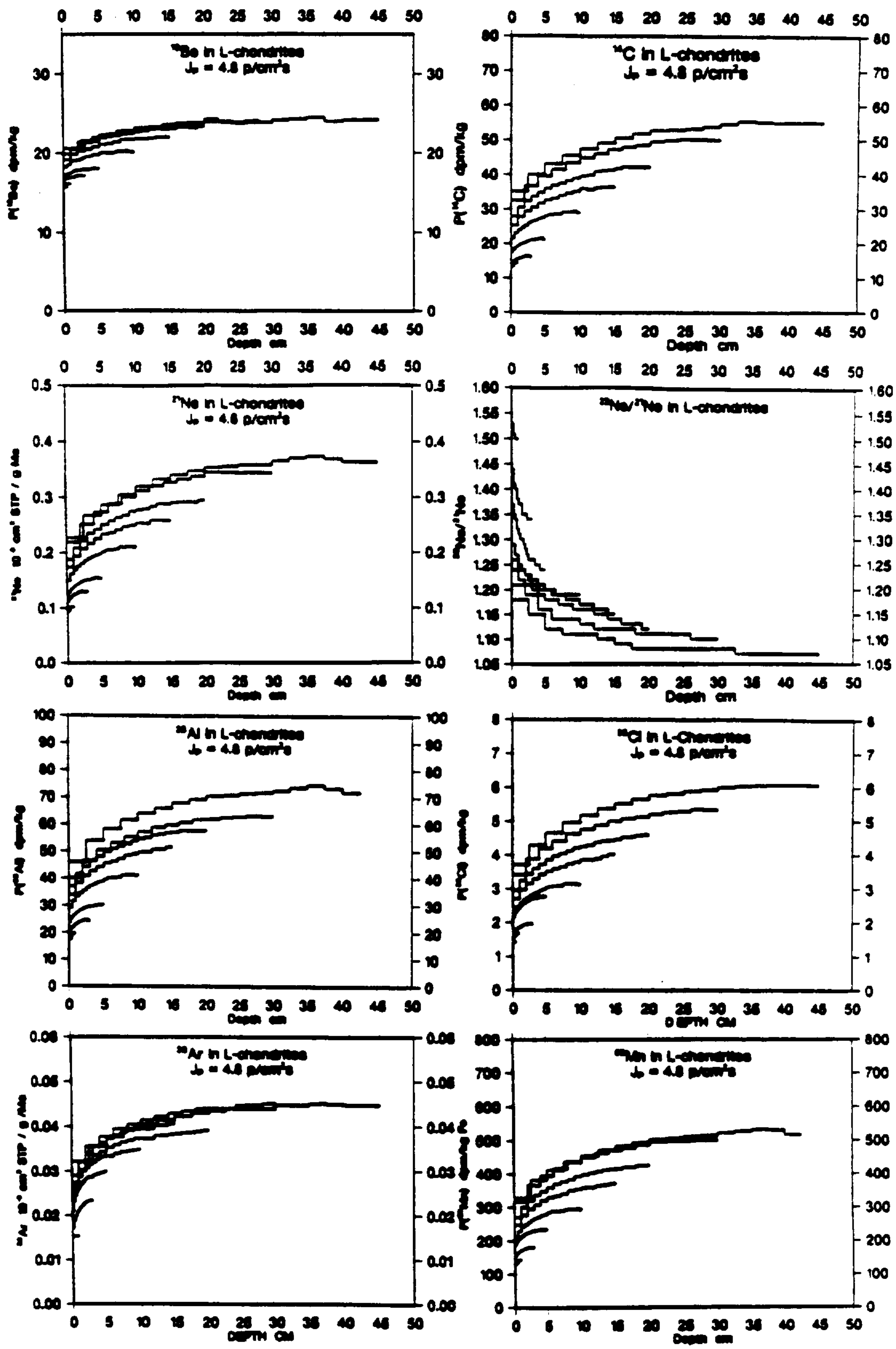

Fig. 1. Calculated GCR production rates (or ratios) as a function of depth in meteoroids of various preatmospheric radii.

a 3-cm sphere and the measured ^{21}Ne concentration [13] yields an exposure age for Salem of about 15 Ma, more than the 9.5-Ma age reported in [5] using systematics based on larger objects, although our calculated $^{22}Ne/^{21}Ne$ ratio (~1.35) is higher than the observed ratio of 1.23. However, this is an upper limit to the age as SCR contributions were not included. Also, possible complications, such as erosion in space [14], have also not been considered.

Except probably for ^{10}Be, which has quite low SCR-production rates [15], it should be remembered that nuclide production by SCR particles should be added to the GCR contribution in interpreting measured concentrations of cosmogenic nuclides. These SCR contributions can be significant, especially near the preatmospheric surface and in the smaller meteoroids [3,7]. The amount of the SCR contribution is not only sensitive to the preatmospheric radius of the meteorite and a sample's preatmospheric depth [3,7], but also to the orbit of the meteoroid prior to hitting the Earth. The time-averaged flux of SCR particles decreases rapidly with increasing distance from the Sun, as R^{-2} because of the distance from the Sun and possibly with poorly known additional factors of up to $R^{-0.5}$ or more due to interactions of SCR particles with the interplanetary medium [16].

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RECOVERY OF THREE ORDINARY CHONDRITES FROM THE NAMIB DESERT IN WESTERN NAMIBIA. A. M. Reid[1], P. Jakeš[2], M. E. Zolensky[3], and R. McG. Miller[4], [1]Department of Geosciences, University of Houston, Houston TX, USA, [2]Department of Geology of Mineral Deposits, Charles University, Prague, Czech Republic, [3]NASA Johnson Space Center, Houston TX 77058, USA, [4]National Petroleum Corporation of Namibia, Windhoek, Namibia.

In 1991 we made reconnaissance searches for meteorites in selected areas of the Namib Desert in western Namibia. The 13 meteorites that have been described from Namibia include the very large Hoba and Gibeon irons and four chondrites (Gobabeb, Namib Desert, St. Francis Bay, and Witsand Farm) that were found in the region of the western desert. To our knowledge the area had not been visited previously with the express purpose of looking for meteorites. Three new ordinary chondrites were recovered as a result of this search.

The Namib is a long narrow desert region in western Namibia, extending approximately 2000 km from the Olifants River in northwestern South Africa to the Carunjamba River in southern Angola. While the determination of the age of desert surfaces is somewhat controversial, there are significant regions in western Namibia with surface ages believed to be at least 5 Ma [1]. Aridity is high throughout the area; however, there is moisture along the Atlantic coastline and immediate interior, due to the common presence of coastal fog banks. The area south of the Kuiseb River includes some of the world's largest dunes.

We made preliminary searches of five different regions in western Namibia: (1) The fan delta and older terraces along the course of the Omaruru River, to the north and east of Henties Bay. Despite the fact that there are deflation surfaces with few coarse rock fragments on these older terraces, no meteorite material was encountered. (2) The older river terraces south of the Swakop River, to the east of Swakopmund. These surfaces are similar to area 1 and no meteorite material was found. (3) Deflation surfaces in the broadly flat-lying region to the east of Walvis Bay, close to the Namibia-South Africa border. In this region three fairly well-preserved ordinary chondrites were recovered. (4) Within the Namib Sand Sea, on deflation surfaces in interdune corridors, between the major longitudinal dunes. The area we examined, lying to the west of Tsondabvlei and south of Gobabeb, is fairly typical of the central desert region, with extremely elongate high dunes alternating with flat interdune corridors. One chondrite, described by Fudali and Noonan [2], has previously been found in this area. While the flat corridors are apparently fairly stable features, we could find no meteorite material within them. (5) The area in and around the Roter Kamm impact crater in the extreme southwest of Namibia, in a remote desert region to the north and west of Rosh Pinah. In examining the crater and collecting crater-related samples, we took the opportunity to search the area for meteorite material, but without success.

Our search method began with the selection of the above regions as having the best potential, and continued with the selection of subareas based on examination of topographic maps, and selection in the field of specific search areas, based on the presence of deflation features and the absence of larger rock fragments and grass cover. Searching was purely visual, with three or four searchers in parallel or random search patterns aimed at examination of all rock fragments greater than a few centimeters in diameter within the selected area.

All five of these areas are prospective collecting sites because of the existence of deflation surfaces of considerable age in a region noted for its extremely arid climate. Reasons for the lack of recovery at four of the sites are related to proximity to the Atlantic coast and the effect of the coastal fogs, to sand movement and the consequent burial of old land surfaces, to our lack of success in recognizing the oldest land surfaces, to the difficulty of recognition of meteorite material (some recovered samples show a surface varnish due to prolonged desert exposure, with embedded quartz grains), and to luck.

The region in which we did recover meteorite fragments is east of Walvis Bay, just within the Namibian border, on a series of deflation surfaces at approximately 23°5.0'S, 14°42.9'E. Each of the meteorites was almost wholly exposed at the surface. Two of the samples were single stones, whereas the third comprised 27 fragments in a area of approximately 2 m^2. The samples are all fairly close to the border station of Rooikop, which may provide an appropriate name for the meteorites.

The largest of the three meteorites is a single severely weathered stone, with thin pervasive Fe oxide veinlets, that weighed 1.039 kg. The sample is an H-group chondrite with constant composition olivine $Fo_{80.9}$, orthopyroxene $Wo_{1.3}En_{81.9}Fs_{16.8}$, clinopyroxene $Wo_{47.1}En_{46.7}Fs_{6.2}$, and plagioclase $Or_{6.3}Ab_{80.5}An_{13.2}$. Minor chromite and phosphate occur along with troilite and metal. Chondrules are generally poorly defined and the meteorite is classified as an H6 [3].

The least weathered of the three meteorites is a single stone that retains a fusion crust and weighed 0.902 kg. The interior surface has prominent chondrules up to 2 mm diameter and the meteorite is an L-group (L4) chondrite with homogeneous olivine $Fo_{76.6}$ and orthopyroxene $Wo_{1.3}En_{77.9}Fs_{20.8}$. Some multiply twinned clino-bronzite is present, along with fine-grained devitrified glass and minor chromite, troilite, and metal.

The third meteorite comprises 27 small fragments with the largest pieces weighing 0.401 and 0.362 kg. It shows well-developed chondrules up to 1 mm diameter, but is weathered with many fine oxide veins. It is also an L-group chondrite (L5) with homogeneous olivine $Fo_{75.4}$, orthopyroxene $Wo_{1.2}En_{76.3}Fs_{22.4}$, and clinopyroxene $Wo_{45.3}En_{46.2}Fs_{8.5}$. Chromite, troilite, and metal are present in minor amounts and there is one occurrence of high-silica glass.

The recovery of three new chondrites is encouraging, considering the vast area for potential meteorite recovery. We are currently trying to organize a follow-up visit to expand the search within the area east of Walvis Bay and explore new search areas.

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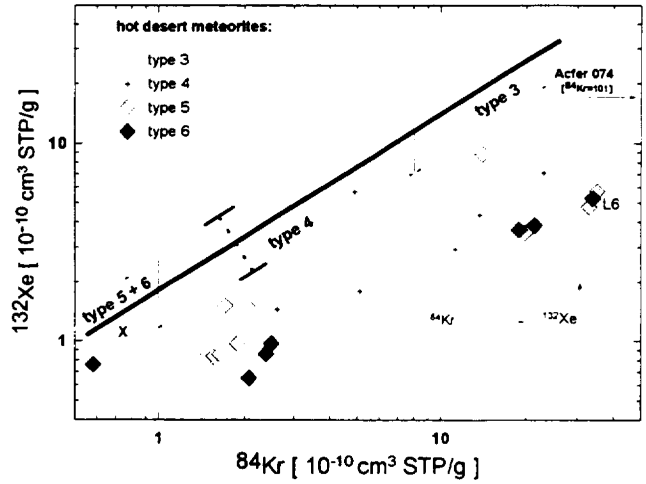

Fig. 1. The concentration of planetary ^{84}Kr and ^{132}Xe in ordinary chondrite falls is correlated with their petrographic-chemical type. The correlation line describes the best linear fit through H3 and H4 falls (data from [3]). The bar in the "type 4" section indicates the range of scattering for the used data points. The investigated hot desert meteorites, however, do not plot along this line. They drift to the right, which is due to an additional contribution of atmospheric gases with a higher Kr/Xe ratio compared to the planetary value. The dotted line indicates, as an example, the replacement from a possible source region in the "type 6" field to the actually measured data point.

WEATHERING AND ATMOSPHERIC NOBLE GASES IN CHONDRITES FROM HOT DESERTS. P. Scherer[1,2], L. Schultz[1], and Th. Loeken[1], [1]Max-Planck-Institut für Chemie, D-55020 Mainz, Germany, [2]Curtin University of Technology, Department of Applied Physics, Perth 6001, Western Australia.

Since the last decade a large number of new meteorites have become available from hot desert regions, mainly from Africa, Australia, and America. Most of these samples are more severely weathered than the relatively fresh specimens found on blue ice fields in Antarctica or modern falls. To determine the weathering grade in the thin section and to investigate the most common alteration products was one aim of this project. Another important purpose of this work was to measure and compare isotopic composition and concentrations of all noble gases in ordinary chondrites from hot deserts with those from other areas and to determine diverging noble gas patterns due to their alteration effects on Earth.

There are three major trapped noble gas components found in ordinary chondrites: the intrinsic planetary gases, solar gases, and terrestrial atmospheric gases as "contamination." These three major components can be separated from each other as well as from *in-situ*-produced cosmogenic or radiogenic gases by the use of their different elemental and isotopic compositions.

Apart from the isotopic composition of Xe, the contribution of atmospheric noble gases is also visible in the concentrations of the heavy noble gases Kr and Xe. As first shown by Zahringer [1] and Marti [2], the petrographic-chemical type of chondrites is correlated with the concentrations of the planetary ^{84}Kr and ^{132}Xe, e.g., type 3 is characterized by $^{84}Kr > 8 \times 10^{-10}$ cm^3 STP/g and types 5 and 6 by $^{84}Kr < 1 \times 10^{-10}$ cm^3 STP/g. The correlation line shown in Fig. 1 is calculated as a best linear fit through data points of H3 and H4 chondrite falls (data from [3]). Almost all chondrites from hot desert regions plot to the right of this correlation line indicating the presence of additional Kr and, to a lesser extent, also Xe. The fact that these samples fall below rather than above the correlation line for uncontaminated specimens is due to the atmospheric $^{84}Kr/^{132}Xe$ ratio of about 28, which is much higher than the planetary value of about 0.6. Acfer 074 (L6), which lies far outside the range of Fig. 1, shows the highest measured ^{84}Kr concentration. With more than 1×10^{-8} cm^3 STP/g it contains about 100× more ^{84}Kr than the Bruderheim (L6) standard.

The concentrations of ^{84}Kr and ^{132}Xe in bulk samples of chondrites from hot desert regions are not consistent within one specimen (Fig. 2). For the Antarctic meteorite Allan Hills 88007 the variation from the mean in the ^{84}Kr concentration is about 13%. In Acfer 019, however, ^{84}Kr varies by about a factor of 2, or from the lowest to the highest value by more than a factor of 6.

The elemental ratios of Ar, Kr, and Xe provide information on the mechanisms of gas incorporation into meteoritic matter. The measured meteorites from hot deserts are plotted together with H-chondrite falls and Antarctic H chondrites (data from [4]) in Fig. 3. This plot reveals that the high Kr concentrations in hot desert meteorites are roughly correlated with low $^{132}Xe/^{84}Kr$ ratios. Most data points are arranged in three clusters. The H-chondrite falls (I)

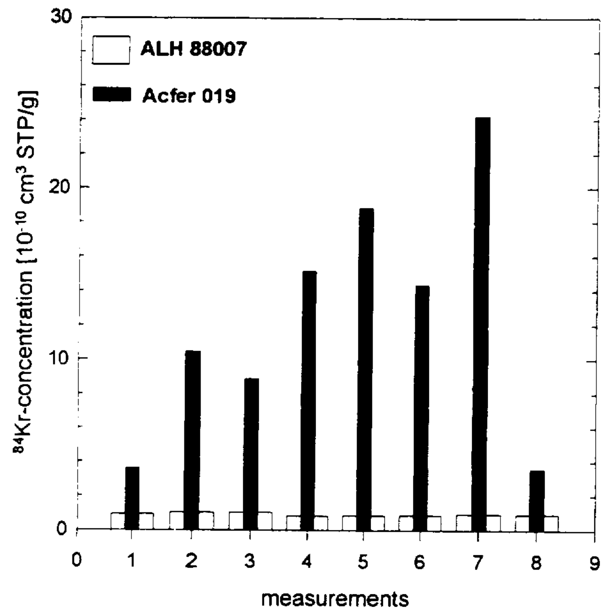

Fig. 2. Variation of the ^{84}Kr concentration in the H5 chondrite ALH 88007 (wide bars) and the hot desert meteorite Acfer 019 (L6) for eight individual measurements.

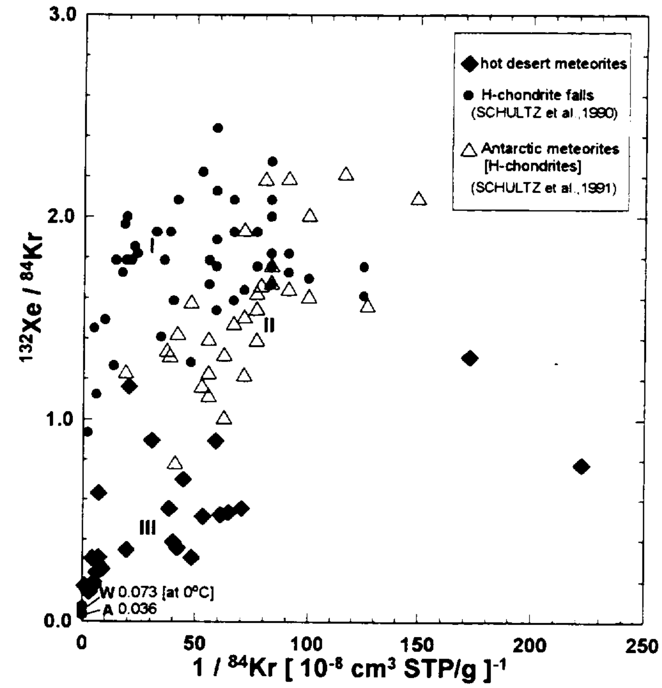

Fig. 3. Three major clusters can be identified in this plot: (I) relatively "fresh" falls, (II) slightly altered Antarctic samples, and (III) the more severely weathered meteorites from hot desert regions. The data points for these highly altered samples drift down to the atmospheric ratio of 0.036. Elemental fractionation is the reason for not reaching this value for the terrestrial atmosphere [A]. The y-axis intercept of about 0.15 for some of the hot desert meteorites lies closer to the ^{132}Xe/^{84}Kr ratio of 0.073 determined for water [W] at 0°C.

as the least-weathered samples plot around the average value for planetary gases in ordinary chondrites with ^{132}Xe/^{84}Kr ~ 1.7. The slightly to moderately weathered Antarctic meteorites scatter between cluster I (falls) and cluster III (measured hot desert meteorites), where most data points intercept the y axis at ^{132}Xe/^{84}Kr ~ 0.15. This ratio is close to the atmospheric value of 0.036, and the fact that the hot desert meteorites never reach this point implies that an elemental fractionation takes place during the process of trapping caused by a higher adsorption coefficient for Xe than for Kr [e.g., 5]. Another explanation is that heavy noble gases are fractionated due to solution in water before incorporation in secondary weathering minerals (e.g., Fe hydroxides or evaporates) that started to build up in the meteorites during their exposure to the surrounding soil and atmosphere on Earth. The latter explanation is supported by, among other things, the fact that the ^{132}Xe/^{84}Kr ratio of 0.15, which is found in severely weathered chondrites from hot deserts, is close to the value of 0.073 determined for water at 0°C [5].

The results concerning the bulk composition of noble gases in chondrites from hot deserts have shown that adsorption in connection with elemental fractionation, possibly together with noble gases dissolved in water, are responsible for the effect of terrestrial contamination in chondrites. The host phases are possibly Fe oxides, Fe hydroxides, and evaporates. This is also seen in the trend that the amount of adsorbed heavy noble gases correlates with the grade of alteration determined in the thin section (weathering classification after [6]).

Several experiments, like the treatment of some hot desert meteorites with oxalic acid or HCl to remove selectively terrestrial alteration products (rust or carbonates), were carried through to get considerable information on the host phases for trapped atmospheric noble gases in chondrites. As a result, most of the acid residues show lowered concentrations of atmospheric Kr and Xe and the Xe isotopic ratios are shifted toward the AVCC composition. The fact that the chemical treatment does not completely remove the atmospheric gases in these samples reveals that there appear to be other additional mechanisms that are responsible for trapping terrestrial noble gases.

Stepwise heating experiments of some samples show that the atmospheric gases cannot be completely removed below temperatures of 1200°C; thus some of the trapped gases are tightly bound. This excludes simple physical adsorption as an explanation for the process that introduces the gases to meteoritic material because preheating the samples at 140°C for at least 48 hr has not removed this component. Niedermann and Eugster [7] describe a process called "irreversible adsorption" for noble gas trapping on mineral surfaces during their crushing in spiked atmospheres. This "anomalous adsorption" probably takes place also in other natural mechanical weathering processes initiated by, among other things, large day and night temperature changes in the hot desert regions. However, the incorporation of noble gases in newly formed secondary weathering products and/or trapping in cavities caused by mechanical and chemical treatment in the laboratory are likely to be important processes that change the original noble gas composition in meteorites.

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EXCURSION GUIDE FOR FIELD TRIP ON JULY 22, 1994.
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Introduction: Both the Ries Crater and the Steinheim Basin (smaller impact structure of 3.5 km diameter and some 40 km southwest of the Ries; see Fig. 2) are located in southern Germany in the center of a triangle formed by the geographical positions of the cities of Munich, Stuttgart, and Nuremberg (see Fig. 1). Both craters are the only impact structures in this area, despite the fact that many other smaller "craters" have been proposed. References [1–17] are a small but representative collection of publications about the Ries impact crater, the Rieskrater Museum Nördlingen, field guides, and maps.

The scientific investigation of this circular structure started 200 years ago. Since then, many theories have been developed to explain the origin of this "hollow" in the south German Jura Mountains. The depression divides this area into the "Suevian Alb" in the southwest and the "Frankonian Alb" in the northeast (see Fig. 2).

For more than a hundred years the interpretation of the volcanic origin of the Ries (the term has its source in the roman name for the "provincia raetia") has been generally accepted. The circular shape of almost 25 km in diameter and the occurrence of a rock containing melted material (suevite) were reasons enough to pursue this idea.

Many other hypotheses about the origin of the basin have been offered in the past. None of them, however, has been able to explain all geological, mineralogical, and geomorphological features in an acceptable combination to get a single explanation of the Ries origin. The concept of the impact of an extraterrestrial body, first mentioned in 1904, could finally be proven by the investigations of Shoemaker and Chao in the early 1960s by the analysis of coesite as a high-pressure polymorph of quartz in local rocks. Together with stishovite, these minerals are typical for rocks in impact craters.

The Ries impact took place almost 15 m.y. ago in the Miocene. An asteroid of almost 1 km in diameter (stone meteorite) hit the Earth with a velocity of at least 70,000 km/h (20,000 m/s) and created an impact structure of almost 25 km in diameter in a very short time (Fig. 2).

Due to the high velocity and sufficient energy (equivalent to 18,000 MT of explosives) the asteroid exploded in a huge fireball and evaporated. Approximately 150 km^3 of rock were destroyed by mechanical break-up, melting processes, and even evaporation,

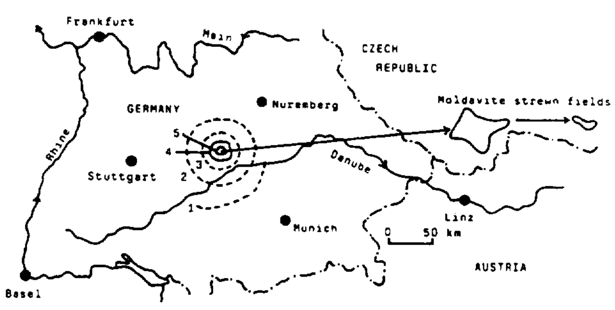

Fig. 1. Map of central Europe showing the location of the Ries and its ejecta. 1 – outer limit of distribution of Malmian Reuter blocks (ejected limestone blocks, sometimes more than 1 m in diameter); 2, 3 – maximum extent of Bunte breccia and suevite respectively; 4 – tectonic rim of the crater; 5 – inner ring; Moldavites – Ries-related tektites (taken from [10], modified).

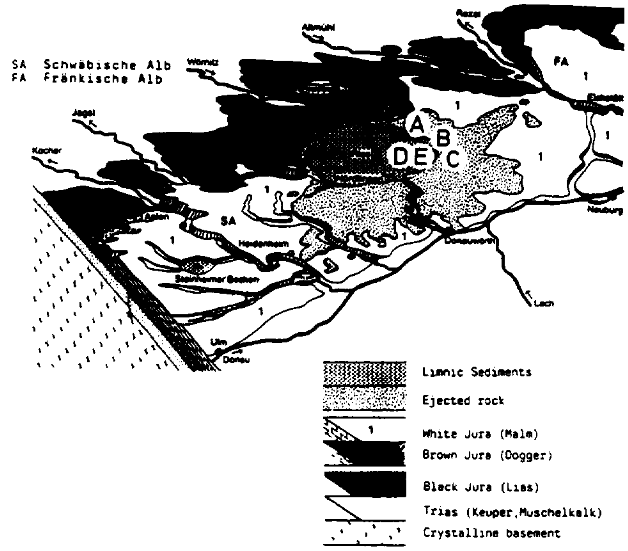

Fig. 2. Block diagram of the Nördlinger Ries and its environment (taken from [13]; blocks A–E refer to soil profiles in [13]).

caused by extremely high short-time pressures and temperatures. All life forms within ~50 km of the impact point were obliterated. The broken and molten rock was deposited inside and around the crater to form vast blankets. The occurrence of an inner ring of lifted basement material (transient crater) is a typical feature of complex craters. The crater itself has been refilled since the impact (lake period) by various types of sediments (clay, sands, lacustrine lime). Subsequently the removal of part of this sediment was caused by tectonic movements at the end of the Tertiary Period by the incision of rivers. The shaping of the basin and its surrounding area is the result of morphodynamic processes during the Pleistocene Period.

Description of Quarries and Outcrops: Figure 3 shows the locations of quarries and outcrops.

Stop No. 1. Two places for a panoramic view across the crater.

Stop No. 1A. Wallerstein outcrop (lacustrine lime). The Wallerstein scar is located in the center of Wallerstein, a small city

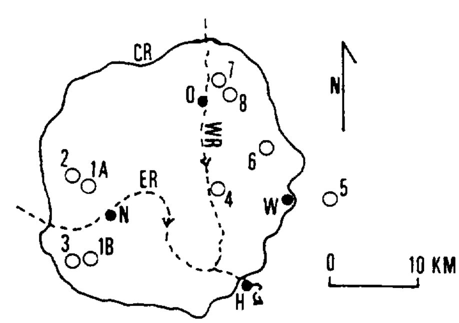

Fig. 3. Geographical distribution of the quarries and outcrops. 1A – Wallerstein outcrop (lacustrine lime; panoramic view). 1B – Siegling quarry (not visited during excursion; panoramic view). 2 – Wengenhausen quarry (shocked basement, lake lime). 3 – Alte Bürg quarry (fallout suevite). 4 – Wennenberg outcrops (inner ring). 5 – Otting quarry (fallout suevite; Bunte breccia). 6 – Polsingen quarry (not visited during excursion). 7 – Aumühle quarry (fallout suevite; Bunte breccia). 8 – Büschelberg quarry (lacustrine lime). CR – crater rim; WR – Wörnitz River; ER – Eger River; N – Nördlingen; O – Oettingen; W – Wemding; H – Harburg.

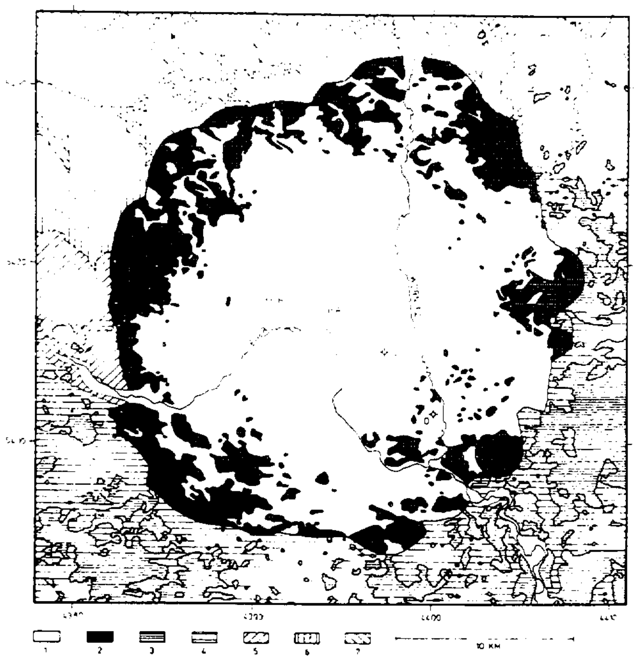

Fig. 4. Geological map of the Ries Crater. A = Center of crater; B = drillhole Nördlingen 1973; C = drillhole Deiningen; D = drillhole Wörnitzostheim. 1 = Post-impact Tertiary and Quaternary sediments, 2 = megablock zone (outcropping), 3 = "Vorries" continuous deposits, 4 = Malmian, 5 = Dogger, 6 = Liassic, 7 = Keuper. 2 and 3 are displaced rocks, 4–7 are autochthonous rocks. This simplified map is based on the Geological Map 1:100,000 (Schmidt-Kaler et al., 1970), on detailed geological maps 1:25,000, and on a preliminary draft for the geological map 1:50,000 (Gall and Muller, 1977).

4–5 km northwest of Nördlingen. It offers a fine panoramic view across the crater. At the top, an elevation of 495 m above sea level (relative to the level of Amsterdam) has been determined. The scar juts out about 75 m from the present basin plane.

Under clear weather conditions various morphological aspects can be observed: (1) The Harburg port in the southeast, where the Wörnitz River leaves the crater basin in a narrow valley through ejected rocks, forming the crater rim. (2) The best-developed part of the crater rim in the east and especially in the south with maximum elevations of about 650 m above sea level (Nördlingen: 435 m). (3) The "Zeugenberge" (monadnocks) of the Ipf near Bopfingen in the east (shaped like a table mountain; contact of the suevian Jura Mountains) and the Heselberg in the north outside the crater. Both these mountains show preimpact geological conditions (horizontal layers, undisturbed rocks). (4) The lower crater rim in the northwest. (5) The incision of the Wörnitz river valley into the northern crater rim, where the river penetrates the Ries plain near Oettingen. (6) The Hahnenkamm Mountains (beginning of the franconian Jura Mountains). (7) Various cone-shaped hills in the Ries plain, which belong to the inner ring (see Stop No. 4). (8) The megablock zone between the inner ring and the structural crater rim. (9) The undulating Ries plain with its settlements and agricultural fields.

The Wallerstein scar belongs to the inner ring. The uplifted basement rocks are covered by lacustrine sediments. A drill hole positioned near the church of Wallerstein brought out a core of these lake sediments of about 30 m on a level of about 450 m north. This means a total thickness of these secondary limestones of about 75 m.

These sediments are rich in fossils. The watersnail *Hydrobia* and the ostracode *Cypris* are lithogenous and indicate a low degree of salinity (soda lake). Sometimes fossilized landsnails (*Cepaea*), mammal bones, bird eggs, and tortoise shells have been found. These animals floated into the lake, where they became fossilized. At the top of the scar and at its base, stromatolites (algae mats built by blue-green algae = cyanobacteria) are exposed.

Stop No. 1B. Siegling quarry (not visited during excursion). The quarry (out of operation) is located approximately 4 km southwest of Nördlingen and west of National Road B 466 (to Ulm) at the northern slope of displaced and accumulated Jurassic limestone. At the eastern side of the road multicolored breccia (Bunte breccia) overlies upper Jurassic allochthonous limestone.

The quarry location offers an impressive view along the southern crater rim.

Stop No. 2. Wengenhausen quarry (shocked basement, lake limestone). The quarry (out of operation) is located 7 km northwest of Nördlingen, close to National Road B 25 (the road from Nördlingen to Dinkelsbühl). It is exposed at the contact of the megablock zone and the inner ring uplift.

The rocks of this quarry are of two different types: (1) Shock-induced, heavily destroyed, and weathered rocks of the crystalline basement (gneisses, amphibolites, granites). This block consists of ejected rock material without any contact with the lifted basement. Dyke rocks occur in the form of so-called "Flecken-Kersantit." Evidence of impact also comes from the occurrence of shatter cones in this dyke rock. (2) The ejected basement material is partly overlain by a thin crust of lake limestone. The bioherm facies (algae-limestone) is apparent with a number of gastropods (land and lake fauna). The lake fauna indicates an alkaline water quality.

Stop No. 3. Alte Bürg quarry (suevite). The old suevite quarry of Alte Bürg (the term means "Old Fort"; quarry out of operation) is located 5 km southwest of Nördlingen close to the crater rim in the territory of Baden-Württemberg.

The quarry is important in two respects: (1) Research history:

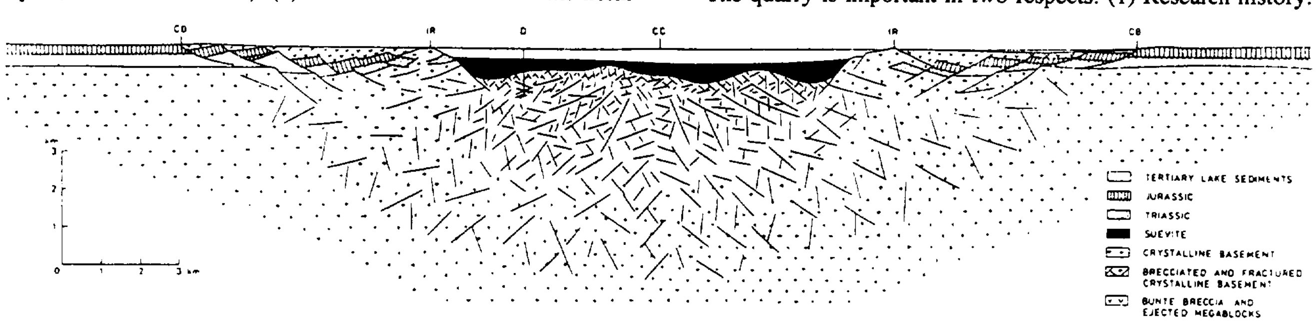

Fig. 5. Schematic cross section of the Ries Crater. No vertical exaggeration. CC = crater center, IR = inner ring, CB = crater boundary, D = drill hole (1206 m; tectonic rim). From [10].

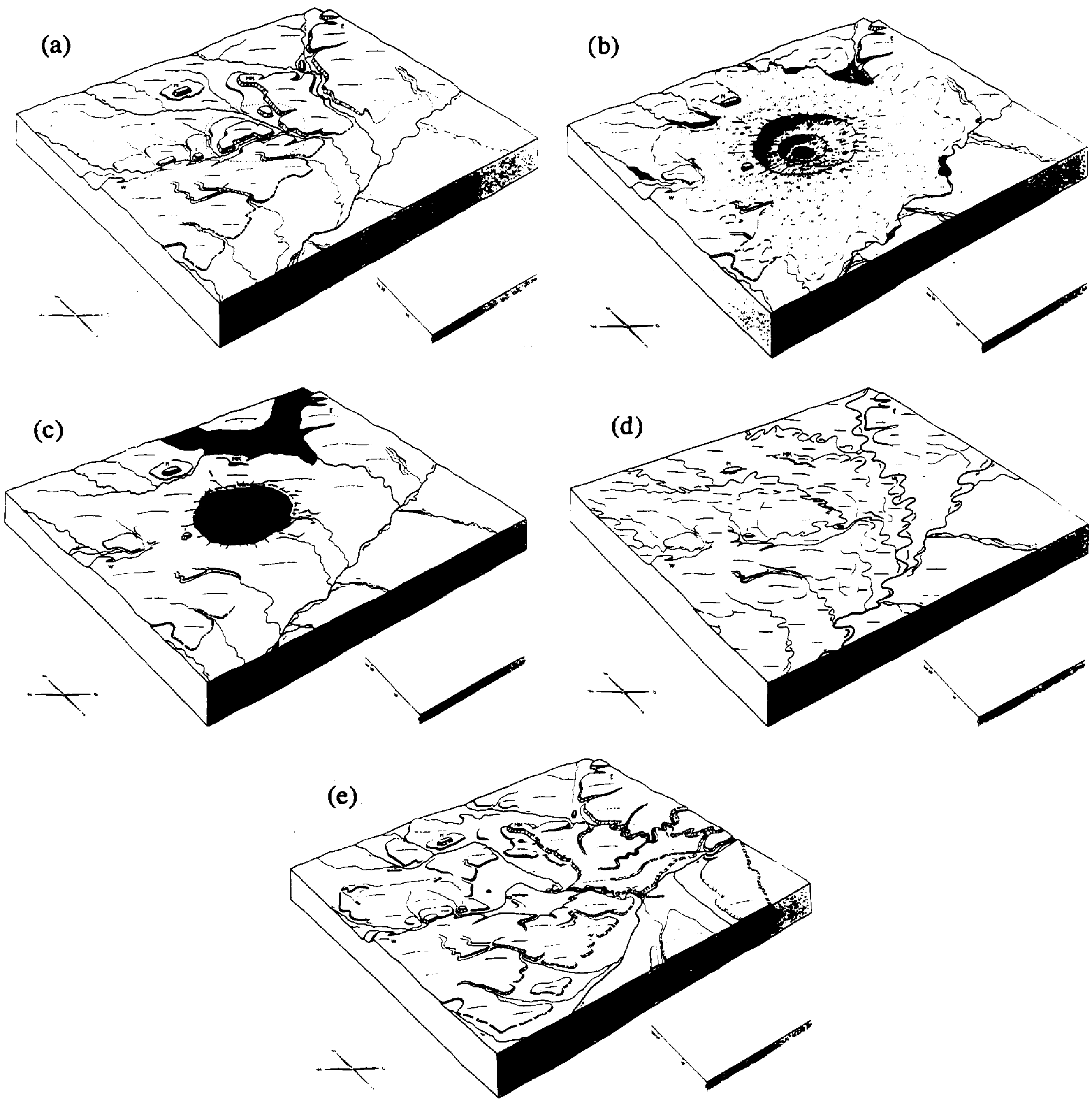

Fig. 6. Stages of landscape development around the crater (explanation in catchwords from [5]). (**a**) Land surface and water courses before impact (15 m.y. ago). West-east escarpment between upper Jurassic rocks in the south and mid Jurassic rocks in the north; suevian Jura Mountains (Suevian Alb in the west) starting with the top layered Ipf (I) near Bopfingen; Franconian Jura Mountains (Franconian Alb in the east) starting with Hahnenkamm Mountains (HK); Zeugenberge (monadnocks): Ipf (I) and Hesselberg (H); main water course: Danube in the south; tributaries: Main and Wörnitz Rivers and others). (**b**) Land surface and water courses after impact (14.5 m.y. ago). Impact crater formation without outlet; blanket of ejected rock in a radius of ~50 km around the crater center; buried water courses and valleys in the vicinity of the crater by fillings of ejected rock material; small lakes dammed by valley capture; extinction of all life forms around the basin. (**c**) Lake period (14.5–12 m.y. ago). Creation of two larger lakes after impact: crater lake (Ries-See), Altmühl-Rezat Lake (dammed Main River; Altmühl and Rezat are two recent rivers); Ries Lake: shallow water, soda lake on an initial stage, episodic water table; continuous filling of the basin by argillaceous and arenaceous sediments; biogene sediments (lacustrine limestones); change of river courses: Wörnitz River tributary to Altmühl-Rezat-lake. (**d**) Phase of basin filling in early Pliocene (~7 m.y. ago). Disappearance of the lakes by sedimentation; vast plains of accumulation in the surrounding areas of the filled crater; beginning of tectonic movements; lifting of the Jura Mountains; initiation of river incision and beginning of removal of basin sediments; change of Wörnitz River course to Danube River. (**e**) Development of present land surface. Tectonism-induced river incision continues and causes removal of ~250 m of basin sediments; lowering of crater bottom; opening of crater walls; excavation of the cone-shaped hills of the inner ring; land forming by morphodynamic processes during the Pleistocene Period; change of Main River course.

The deep weathered suevite is exposed in a vertical contact with malmian allochthonous limestone (stratified displaced megablock). In former times this contact was explained as the exposure of a volcanic pipe filled with the "Ries Trass" (suevite) as a volcanic rock. In fact, this quarry represents the type of locality for the theory of the "volcanic" origin of the Ries Crater. (2) Building history: Besides other buildings in the city of Nördlingen and elsewhere, the St. George Church was completely built with suevite. The rock for this building was broken in Alte Bürg quarry.

Stop No. 4. Wenneberg outcrops (inner ring). The Wenneberg is located 10 km east of Nördlingen as a cone-shaped hill, partly covered with forest. It belongs to the inner crystalline ring with a continuous contact to the basement (lifted rock, no ejection). In this basement rock, exposed in a small disused quarry, "wennebergite" (a type of kersantite; see Stop No. 2) occurs as a dyke in porphyric biotite granite and amphibolite matrix. Besides this exposure "wennebergite" is only known as fragments of bedrocks in the eastern part of the crater.

The crystalline basement rocks are covered by lacustrine sediments, especially exposed at the eastern side of the hill. Again the occurrence of the watersnail *Hydrobia* and the ostracode *Cypris* (the fossils are rockforming) indicates a low degree of salinity of the former crater lake.

A 30-minute walk around the hill offers another opportunity for a panoramic view across the crater, especially of its eastern part.

Stop No. 5. Otting quarry (fallout suevite, Bunte breccia). This suevite quarry is currently out of operation, and is located northwest of the village of Otting, approximately 5 km east of Wemding and the crater rim (distance to Nördlingen, 25 km). On account of its hydraulic properties, suevite is used as an additive for the production of cement. Concrete produced with this cement has better resistance against corrosion (e.g., compare the use of pumice from Santorini Island, Greece, during the construction of the Suez Canal).

The Otting quarry is one of the best known and largest in the vicinity of the Ries Crater for studying suevite and the typical postimpact stratigraphy. The rock sequence is characterized by underlying limestone (Malm delta) covered by a striated surface slide caused by the displacement of huge blocks of rock. The surface slide is overlain by Bunte breccia, followed by suevite. As revealed by some drillholes especially in the northern part of the quarry, the suevite has a maximum thickness of 24 m, the Bunte breccia of only a few meters to almost 200 m east of the quarry (see below).

Otting quarry is well known for the opportunities for collecting fresh, unweathered suevite samples containing vesiculated glass bombs and basement rock fragments (up to 98 vol%) of all stages of shock metamorphism (see Tables 1 and 2). The basement material consists of magmatic rock (granite) and metamorphic rock (gneisses, amphibolite). The portion of sedimentary rock is only 2% or less with mostly very small fragments. Finely distributed lime of secondary origin occurs, forming calcite crystals at the walls of the vesicles.

The quarry is important with regard to two aspects of research history: (1) In 1960 Eugene Shoemaker collected some rock specimens here to deliver to Ed Chao. By analyzing these samples, Chao found shocked-quartz-bearing crystalline rock portions that contained high-pressure polymorphs of quartz: coesite and stishovite. This result was decisive for the explanation of the Ries Crater as an impact structure. (2) It turned out that the vesicles in the glass bombs (molten acidic basement material) contained the noble gas ^{40}Ar. This gas is a decay product of ^{40}K (half-life 1300 m.y.). By comparing the amount of both these elements, the age of the impact structure could be determined to be 14.8 ± 0.7 m.y. [6]. A more accurate age of 15.0 ± 0.1 m.y. has been found by [14] by using the ^{40}Ar-^{39}Ar method.

TABLE 1. Stages of shock metamorphism (from [7]).

Shock Stage	PRESSURE p (kbar)	Post-shock temperature T (°C)	RANGE R(km) $p \sim R^{-3.75}$ to $R^{-3.0}$	SHOCK EFFECTS	Occurence in:
V	> 800	> 3000	0.0 - 1.0	VAPORIZATION	
IV	800 - 600	3000 - 1700	1.0 - 1.1	COMPLETE MELTING OF ROCKS Mixing of melts; lechatelierite	Suevite
III	600 - 450	1700 - 900	1.1 - 1.2	SELECTIVE FUSION OF FELDSPAR GLASS (plagioclase melts at higher temperatures than potassium feldspar) Quartz: diaplectic glass with coesite Amphibole, pyroxene, biotite: thermal decomposition	Suevite
II	450 - 350	900 - 300	1.2 - 1.3	DIAPLECTIC GLASSES of quartz and feldspar; Coesite and stishovite in quartz Amphibole, pyroxene: deformation lamellae Biotite: kink bands	Suevite Polymikt breccia (Bunte Breccia)
I	350 - 100	300 - 100	1.3 - 1.8	DIAPLECTIC CRYSTALS with planar deformation features in tectosilicates: quartz > 100 kbar, plagioclase > 150 kbar Amphibole, pyroxene: planar elements perpendicular to NZ Biotite: kink bands	Suevite Polymikt breccia (Bunte Breccia)
0	100 - 10	100 - 0	1.8 - 3.6	FRACTURING OF MINERALS AND Biotite: kink bands (> 10 kbar) Amphibole, pyroxene: planar elements SHATTER CONES	Suevite Polymikt breccia Bunte Breccia Megablocks

TABLE 2. Impact formation of the Ries Crater (from [10]).

Impact formation	Particle size (m)	Stratigraphic provenance	Shock metamorphism	Geological setting	Texture
Impact melt	As inclusions < 0.2–0.5 m	Crystalline rocks	Stage IV 550–1000 kbar	As inclusions in suevite or as larger coherent bodies	Polymict (mixed with rock and mineral clasts)
Suevite	< 0.2–0.5 m	Crystalline rocks ≫ sedimentary rocks	Stages 0–IV < ~ 1000 kbar	Central crater cavity, megablock zone, and Vorries zone	Polymict
Dike breccias	< 0.2–0.5 m	Crystalline rocks ≫ sedimentary rocks	Stages 0–II < ~ 350 kbar	Crater basement megablocks, surface megablocks	Polymict
Crystalline breccia	< 0.5–1 m	Crystalline rocks	Stages 0–II < ~ 350 kbar	As irregular bodies within or on top of Bunte breccia, central crater cavity	Polymict
Bunte breccia	< 25 m	Sedimentary rocks ≫ crystalline rocks	Stages 0–II < ~ 350 kbar	Megablock zone and Vorries zone	Polymict
Megablocks	~ 25–1000 m	All stratigraphic units	Stages 0–I < ~ 50–100 kbar	Crater basement, inner ring, megablock zone and Vorries	Monomict
Brecciated and fractured autochthonous rocks	—	All stratigraphic units	Stage 0 < ~ 50 kbar	At the tectonic rim, undisplaced crater basement	Monomict

Underlying the suevite, the ejected sediments (Bunte breccia containing brecciated rock of upper Triassic and Jurassic age) occur in various thicknesses up to almost 200 m. This is the case where the preimpact Main River valley (today a Rhine River tributary) has been filled and dammed by the ejected sediments. This former river valley had a more or less north-south-headed course with its mouth into the Danube near the city of Donauwörth.

Stop No. 6. Polsingen quarry (impact melt breccia; not visited) is a small old quarry no longer in operation in the so-called "red suevite" near the village of Polsingen, some 5 km northwest of Wemding. The melt breccia is quite remarkable, for the whole matrix consists of molten material. This fine-grained matrix is loaded with crystalline rock fragments of various stages of shock metamorphism. Inclusions of sedimentary fragments have not been observed. Coesite occurs. The typical red color of the vesiculated melt matrix is caused by finely distributed hematite. This rock, which once was explained as a component of a lava lake of volcanic origin, only occurs in a similar form here and near Amerbach (south of the crater), which is not more exposed.

Stop No. 7. Aumühle quarry (fallout suevite overlying Bunte breccia) is located at the northern crater rim 2.5 km north-northeast of the city of Oettingen and is in operation (suevite is used as an additive for cement production).

The suevite of this quarry overlies Bunte breccia, which shows a hummocky surface structure. It contains numerous glass bombs with a sometimes reddish color. Basement fragments are abundant. The corn size of the matrix, the size of the glass bombs, and the basement fragments vary greatly. The rock is partly deep weathered with a rather frequent occurrence of degassing pipes (here yellowish montmorillonitic clay minerals).

The Bunte breccia consists of various sediment fragments (clay, sandstone) of upper Triassic and lower and mid Jurassic age. The colors show a great deal of variety: purplish-red and white for the upper Triassic sandstones, dark-colored lower Jurassic clay, and red mid Jurassic sandstone. The roll-glide mechanism is clearly visible from the turbulent features in the sediments. The rock contains many fossils, especially the shocked and sliced grains of the so-called "Ries-Belemnites."

Stop No. 8. Büschelberg quarry (lacustrine lime), out of operation, is located at the northern crater rim near Hainsfarth, 2 km east of Oettingen, and is under nature conservation.

The wide-range quarry represents one of the largest distributions of exposed lacustrine lime of the Ries Crater. On the surface the quarry walls are 6–7 m high.

Two different types of facies are exposed at this northern margin of the crater lake: (1) an algal biotherm facies, represented by root-

TABLE 3. Deep burst model of the Ries impact (modified after [7]).

Projectile:	Diabase-like stone asteroid; diameter 1000 m; density 3.0 g/cm³; velocity 20 km/s; kinetic energy E = 1.64* 10²⁰ joule
Target:	Granite-like and sediments
Initial pressure:	660 GPa
Transient crater:	Parabolic profile in the basement ($y^2 = 9.29 * 10^3 x$); maximum depth in the center 2780 m below surface (shock pressure 25 GPA); radius at basement/sediment boundary 4500 m (shock pressure 0.5 GPa); radius at the surface 12,000 m (shock pressure 0.2 GPa); diameter/depth ratio: surface 4.3, basement 4.1

Volumes of vaporized, melted, shocked, and excavated rock.

Stage	Shock Pressure GPa	Basement (km^3)	Sedim. (km^3)	Total (km^3)
V	>100	3.54	0	3.54
IV	100–60	1.45	0	1.45
III	60–45	1.03	0.02	1.05
II	45–35	1.28	0.03	1.31
I	35–10	11.4	0.12	11.52
0	<10	51.0	67.5	118.5
Excavated volume (km^3)		69.4	67.9	137.5
Excavated mass (10^{11}t)		1.96	1.63	3.59

shaped bodies that can be combined to greater cone-shaped components (bundles), sometimes 1–2 m in diameter; (2) between the bundles a sedimentary facies is developed, formed by the accumulation (rock forming) of numerous individuals of the watersnail *Hydrobia* and the ostracode *Cypris* (again an indication of low salinity).

For further information about the geological structure of the crater, the distribution of rocks, the description of rock types, their characteristics, and the stages of landscape development we refer to the list of references and to Figs. 4, 5, and 6a–d and Tables 1–3.

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COSMOGENIC BERYLLIUM-10 AND ALUMINUM-26 IN LEWIS CLIFF METEORITES.

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Introduction: Terrestrial ages of Antarctic meteorites give information about the age of the stranding surface they are found on and may provide more insight into the concentration mechanisms involved. In this way, Antarctic meteorites contribute to a better understanding of the history of the Antarctic ice sheet [1], which is of special interest because most stranding surfaces are found in those regions where the ice sheet is very sensitive to climate changes [2]. One of the most "productive" blue ice fields is the Lewis Cliff stranding area (84°15' S, 161°30' E), which is located between Law Glacier and Beardmore Glacier, two major outlet glaciers near the Queen Alexandra Range. So far, it has yielded more than 1800 meteorites, most of which were found on the Lewis Cliff Ice Tongue, a small blue ice field of 2.5 × 8 km. Earlier ^{26}Al measurements on 30 meteorites [3]—as part of an ongoing γ-ray survey—and ^{36}Cl AMS measurements on 8 meteorites [4] suggest that the Lewis Cliff area is a relatively old stranding surface.

Here we present ^{26}Al γ-ray results of 85 Lewis Cliff ordinary chondrites (OCs), obtained by measurements on bulk samples of 30–500 g. These results will be compared with those of 557 OCs from the Allan Hills Ice Fields [5] in order to determine the relative age of the Lewis Cliff stranding area. The relationship between the ^{26}Al activity and the location of find on the ice will be discussed to shed more light on the local meteorite concentration mechanism. For 67 Lewis Cliff OCs the ^{26}Al activities will be compared with available natural thermoluminescence (NTL) data [6] in order to test their previously suggested relationship (both ^{26}Al and NTL decrease with terrestrial age) and to identify meteorites with unusual exposure histories. On the basis of our γ-ray results, material was selected for subsequent AMS measurements of ^{10}Be, ^{26}Al, and ^{36}Cl. Here we present AMS results for ^{10}Be and ^{26}Al of 29 Lewis Cliff samples. The combination of ^{26}Al with ^{10}Be data allows a better estimate of the terrestrial ages of these meteorites because corrections can be made for short exposure ages where necessary. Finally, we used our γ-ray and AMS results to identify potential pairings.

Experimental: *Gamma-ray measurements.* For bulk samples of 30–500 g γ-ray spectra were measured for 5–15 days by high-purity Ge detectors of either 110 cm^3 or 90 cm^3. Efficiency calibration curves were made, based on 16 meteorite mock-ups of different size and shape. The mock-ups were made of a thin araldite shell, filled with a mixture of ointment and Cu powder, thus matching both the specific gravity and electronic density of ordinary chondrites. Known amounts of KCl and ^{26}Al were added to the mixture in order to calibrate the efficiency of the 1.46 MeV γ– line of natural ^{40}K and the 1.81 MeVγ-line of cosmogenic ^{26}Al. The calibration curve adds an uncertainty of 2–4% to the statistical uncertainties, which are 5–10% for ^{26}Al and 2–5% for ^{40}K. The natural ^{40}K activities are used to deduce the K content of the meteorites.

AMS sample preparation. Chondrite samples of about 1 g were crushed in an agate mortar. The metal phase was separated from the nonmagnetic silicate fraction by hand with a magnet. The silicate fraction was further homogenized and used for ^{10}Be and ^{26}Al measurements, while the metal phase was kept for ^{36}Cl analysis. We added 1.0 ml of Be and Al standard solutions (Merck, 1000 ± 2 mg/l) to silicate subsamples of 40–60 mg. Dissolution of the samples and chemical preparation of BeO and Al_2O_3 targets was carried out as described previously [7].

AMS measurements. The ^{10}Be and ^{26}Al measurements were carried out at the Utrecht AMS facility [7]. Both isotopes were measured routinely using a fast beam-switching method, resulting in precisions of 1–2% for the $^{10}Be/^{9}Be$ ratios and 2–4% for the $^{26}Al/^{27}Al$ ratios. In addition, the precision of the resulting ^{26}Al content is affected by the uncertainty in the indigenous ^{27}Al content of a meteorite sample. From bulk Al contents [8] and a correction for average metal contents of 9% for L chondrites and 17% for H chondrites, we estimated the average Al content of the silicate fraction of H and L chondrites at 13.5 ± 1.3 mg/g. The addition of extra Al carrier reduced the uncertainty in the total amount of ^{27}Al to 4%.

Results and Discussion: *Aluminum-26 γ-ray survey.* General distribution of ^{26}Al contents: Table 1 lists the measured ^{26}Al γ-ray activities and K contents of 85 Lewis Cliff OCs. Figure 1 shows the distribution of their ^{26}Al activities, compared with that of 557 specimens from the Allan Hills region [5]. All H chondrite activities were normalized to L chondrite composition by multiplying by a factor of 1.07. It should be noted that neither histogram has been corrected for pairings. The ^{26}Al activities range from 23 to 75 dpm/kg, except for two meteorites with values of 7 and 96 dpm/kg, respectively, which are unusual in comparison to the average saturation value of 60 dpm/kg. These and other anomalous cases will be discussed separately. The Lewis Cliff distribution of ^{26}Al activities shows a broad peak between 35 and 55 dpm/kg, well below the saturation value of 60 dpm/kg. Although some of these low values might be due to short exposure ages—as will be shown later—or irradiation in space as small objects, it seems plausible that many of these meteorites have terrestrial ages of 100 k.y. or more. Figure 1 also illustrates that the Lewis Cliff OCs peak at lower ^{26}Al activities than the Allan Hills OCs, suggesting that the Lewis Cliff stranding area harbors older, on the average, meteorites and thus has been in operation for a longer period than the Allan Hills area, the oldest stranding surface thus far known. Interestingly, most of the meteorites from the Lewis Cliff Ice Tongue were found on the western side, on relatively old ice, which was formed under the very cold climatic conditions of a glacial period, as indicated by its very low $\delta^{18}O$ values (–53 to –58‰) [9]. However, for the Lewis Cliff meteorites investigated thus far, we found no obvious relationship between their ^{26}Al activity and the location on the ice field [10]. This hints at a complex glaciology of the Lewis Cliff stranding area, as was suggested previously on the basis of field observations [1].

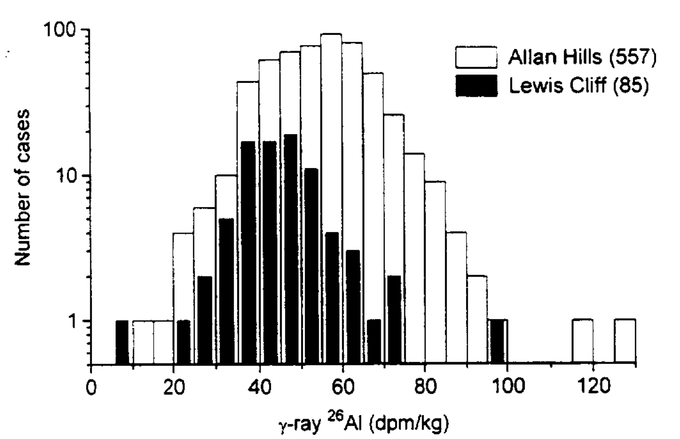

Fig. 1. ^{26}Al in Antarctic ordinary chondrites.

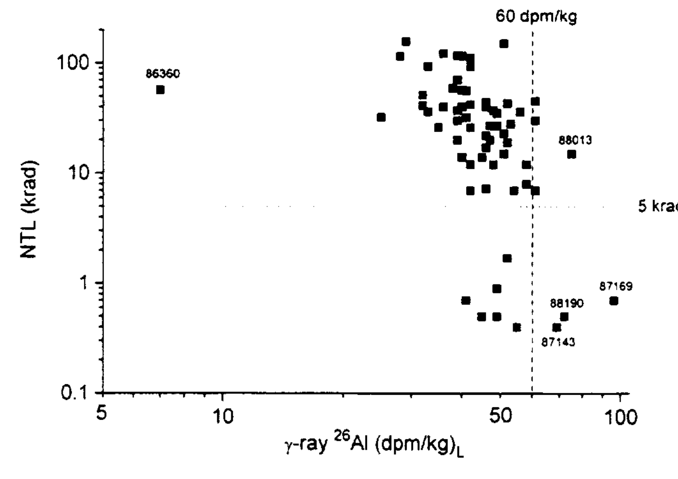

Fig. 2. NTL vs. ^{26}Al for 67 Lewis Cliff OCs.

NTL vs. ^{26}Al contents: Thermoluminescence studies [6] were carried out on 67 of the 85 Lewis Cliff samples that we measured in our γ-ray survey. Figure 2, which shows the combined ^{26}Al (L-normalized) and NTL results for these samples, reveals two main groups: one with high NTL values (>5 krad) and one with low NTL values (<2 krad). The high-NTL group exhibits two outliers, one with a ^{26}Al activity of 7 dpm/kg and one with 75 dpm/kg. The low-NTL group, however, contains a relatively high number of 3 (out of 9) meteorites with unusual, "oversaturated" ^{26}Al values, as will be explained later. Except for the outliers, the high-NTL group shows ^{26}Al values between 20 and 60 dpm/kg. Contrary to earlier reports [6], there is no obvious correlation between NTL values and ^{26}Al activities. This indicates that for Lewis Cliff meteorites the NTL value is not even roughly related to the terrestrial age. More recently, it was indeed argued that the NTL level of an Antarctic meteorite is largely determined by its "surface exposure age" rather than its total terrestrial age [12]. This still does not explain the negative—rather than positive—correlation we observe between NTL and ^{26}Al in Lewis Cliff meteorites.

Unusual exposure histories: The lowest ^{26}Al activity of 7 ± 2 dpm/kg found in LEW 86360 (L4) hints at either a very high terrestrial age (≥2 Ma), an extremely short exposure age («1 Ma) or a complex exposure history. The latter explanation seems most likely, as was also concluded for the Antarctic meteorite ALH 76008 with a similarly low ^{26}Al activity of 11 ± 1 dpm/kg [11]. Beryllium-10 and noble gas measurements are currently in progress to shed

TABLE 1. ^{26}Al γ-ray activity, K content, NTL data, and pairing of 85 Lewis Cliff OCs.

H-CHONDRITES							L,LL-CHONDRITES						
LEW	Type	Grid[a]	^{26}Al[b]	K (mg/g)	NTL[c]	Pair[d]	LEW	Type	Grid[a]	^{26}Al[b]	K (mg/g)	NTL[c]	Pair[d]
88019	H4	NB-8	38 ± 2	.74 ± .03	56	1,a	86022	L3	NB-7	49 ± 4	.96 ± .05	< 1	x
88020	H4	NB-8	37 ± 3	.68 ± .04	57	1,a	86021	L3	NG-3	32 ± 3	.77 ± .05	36	x
88174	H4	NF-3	37 ± 3	.65 ± .03	116	1,b	86018	L3	SM-10	45 ± 3	1.17 ± .05	< 1	x
88163	H4	NF-4	36 ± 3	.75 ± .04	-	1,b	86014	L4	NH-3	42 ± 3	.87 ± .04	93	x
86250	H5	NH-4	57 ± 4	.76 ± .04	45	x	86024	L4	SO-8	46 ± 3	.83 ± .03	22	x
88022	H5	NF-4	48 ± 3	.85 ± .04	-	2,c	86360	L4	SL-11	7 ± 2	.73 ± .03	57	x
88116	H5	NG-3	46 ± 3	.70 ± .04	-	2,c	85343	L4	SL-5	40 ± 3	.94 ± .05	40	10,c
86518	H5	NC-5	43 ± 3	.72 ± .04	-	2,c	88021	L4	SK-3	38 ± 3	.78 ± .04	-	10,c
86534	H5	NF-7	37 ± 4	.63 ± .06	14	x	85340	L5	SO-3	47 ± 3	.89 ± .04	27	x
86083	H5	SM-9	53 ± 3	.96 ± .03	36	3,c	88017	L6	NE-5	51 ± 3	.94 ± .04	23	11,c
86371	H5	SL-11	50 ± 3	.83 ± .04	25	3,c	86025	L6	ND-7	49 ± 5	.87 ± .05	0.9	x
87261	H5	SL-12	47 ± 3	.95 ± .07	-	3,c	88164	L6	ND-6	49 ± 3	.75 ± .04	-	11,c
85471	H5	SO-10	43 ± 3	.73 ± .03	40	4,c	88177	L6	NE-5	46 ± 3	.84 ± .04	-	11,c
86031	H5	SL-11	40 ± 3	.84 ± .05	127	4,b	88169	L6	NF-6	45 ± 3	.86 ± .04	-	11,c
86086	H5	SM-9	39 ± 3	.79 ± .04	93	4,b	88016	L6	NG-4	42 ± 2	.76 ± .03	111	12,b
87041	H5	SL-12	36 ± 3	.84 ± .04	117	4,b	88058	L6	NE-6	39 ± 3	.71 ± .04	70	12,b
87210	H5	AJ-3	40 ± 3	.79 ± .03	45	x	86490	L6	NG-3	38 ± 3	.74 ± .03	59	12,b
88013	H5	SM-3	70 ± 4	.73 ± .03	15	x	85323	L6	MM	61 ± 3	.89 ± .03	6.6	x
85327	H5	SJ-2	52 ± 3	.63 ± .05	0.37	x	86016	L6	SO-9	58 ± 5	.66 ± .06	8.2	x
85326	H5	SO-4	48 ± 3	.87 ± .03	151	x	86085	L6	SN-9	52 ± 3	.88 ± .03	19	x
85319	H5	SJ-4	43 ± 4	.75 ± .04	7.3	5,b	85325	L6	SP-10	47 ± 4	.75 ± .05	20	x
85341	H5	SO-3	42 ± 3	.82 ± .05	14	5,c	87199	L6	SL-11	36 ± 3	.94 ± .04	-	x
85338	H5	SJ-4	39 ± 3	.77 ± .04	26	5,b	86013	L6	SM-10	33 ± 2	.85 ± .03	93	13,a
85318	H5	UIT	39 ± 2	.73 ± .03	12	5,b	86012	L6	SM-10	32 ± 2	.88 ± .04	51	13,a
86312	H5	SQ-2	37 ± 3	.66 ± .04	20	5,c	86011	L6	SN-9	29 ± 2	.78 ± .05	157	13,a
85334	H5	SK-4	33 ± 2	.67 ± .03	26	5,c	86019	L6	SM-10	28 ± 3	.77 ± .08	115	13,a
85324	H5	SO-3	23 ± 3	.71 ± .04	32	x	87169	L6	AJ-4	96 ± 4	.91 ± .04	0.7	x
87034	H5	UWN	57 ± 5	.63 ± .06	30	6,c	87143	L6	AH-4	69 ± 4	.92 ± .05	0.4	x
87030	H5	UWN	54 ± 4	.80 ± .05	12	6,c	87196	L6	AJ-4	53 ± 4	.81 ± .04	-	14,c
87043	H5	UWN	38 ± 3	.76 ± .03	0.65	x	87046	L6	AI-4	49 ± 2	.70 ± .03	27	14,b
86015	H6	NI-3	33 ± 2	.77 ± .04	122	x	87035	L6	AJ-3	49 ± 3	.78 ± .05	35	14,b
87047	H6	AI-5	51 ± 3	.80 ± .04	6.9	7,c	87042	L6	AJ-4	48 ± 3	.76 ± .04	37	14,b
87050	H6	AH-5	50 ± 3	.84 ± .03	-	7,c	87040	L6	AH-5	46 ± 4	.79 ± .05	44	14,b
87039	H6	AI-5	48 ± 4	.83 ± .04	43	7,c	87175	L6	AI-3	44 ± 3	.78 ± .03	-	14,c
87048	H6	AI-4	48 ± 3	.79 ± .04	1.7	x	86023	L6	AG-7	41 ± 4	.62 ± .06	32	x
87194	H6	AH-4	35 ± 3	.69 ± .04	-	x	87036	L6	AH-5	39 ± 3	.91 ± .04	37	15,b
86017	H6	AC-4	43 ± 2	.80 ± .03	17	x	87045	L6	AJ-4	39 ± 2	.71 ± .02	30	16,c
85330	H6	SK-3	45 ± 4	.62 ± .05	12	8,c	87174	L6	AI-4	37 ± 3	1.00 ± .04	-	15,b
85335	H6	SO-3	39 ± 2	.71 ± .03	6.9	8,c	87038	L6	AI-4	36 ± 3	.73 ± .04	40	15,c
85329	H6	UIT	39 ± 2	.63 ± .03	26	8,c	87247	L6	AI-5	35 ± 3	.70 ± .04	-	16,c
88198	H6	SN-3	34 ± 3	.77 ± .03	-	9,c	88190	L6	SN-4	72 ± 3	.84 ± .03	0.5	x
85322	H6	SL-4	29 ± 3	.81 ± .05	41	9,c	88018	L6	SP-2	51 ± 3	.94 ± .03	15	x
							87279	LL6	AI-4	42 ± 3	.70 ± .04	42	x

[a]) Grid cell (0.5x0.5 km): NB3-NI8 = Lower Ice Tongue (LIT), SJ2-SQ5 = Upper Ice Tongue (UIT), SN9-SL12 = Meteorite Moraine (MM), Grid Cell (2x2 km): AH3-AJ5 = South Lewis Cliff, UWN = Upper Walcott Névé, [b]) ^{26}Al in dpm/kg, [c]) NTL in krad at 250 °C from Benoit et al. [6], [d]) pairing group number 1-16, confidence level a (probably), b (tentatively), c (possibly) and x (unpaired) [16].

TABLE 2. ^{10}Be and ^{26}Al contents of 29 Lewis Cliff OCs and Utrecht L6 chondrite.

Sample	Type	Fraction	^{10}Be (dpm/kg)^{a} Silicate	^{10}Be (dpm/kg)^{a} Bulk^{c}	^{26}Al (dpm/kg)^{b} Silicate	^{26}Al (dpm/kg)^{b} Bulk^{c}	A^{26}/A^{10}
LEW 85319.79	H5	Silicate	15.1 ± 0.1	13.0 ± 0.1	55 ± 3	45 ± 2	3.46 ± 0.17
LEW 85320.105	H5	Silicate	19.1 ± 0.3	16.5 ± 0.2	57 ± 3	56 ± 3	3.36 ± 0.17
LEW 85324.16	H5	Silicate	6.81 ± 0.10	6.00 ± 0.10	30.7 ± 1.5	26.1 ± 1.3	4.35 ± 0.23
LEW 85324.16	H5	Bulk	-	6.44 ± 0.15	-	24.5 ± 1.9	3.80 ± 0.33
LEW 85326.14	H5	Silicate	14.3 ± 0.1	13.3 ± 0.1	54 ± 3	49 ± 2	3.67 ± 0.18
LEW 85327.15	H5	Silicate	20.6 ± 0.3	17.5 ± 0.3	68 ± 3	56 ± 3	3.17 ± 0.16
LEW 85327.15	H5	Bulk	-	17.2 ± 0.3	-	61 ± 4	3.55 ± 0.24
LEW 86312.11	H5	Silicate	15.9 ± 0.2	13.5 ± 0.1	43 ± 2	35 ± 2	2.56 ± 0.13
LEW 86518.5	H5	Silicate	18.0 ± 0.2	16.4 ± 0.1	47 ± 2	42 ± 2	2.55 ± 0.13
LEW 86534.13	H5	Silicate	14.8 ± 0.2	13.7 ± 0.2	59 ± 3	52 ± 3	3.80 ± 0.19
LEW 86534.13	H5	Bulk	-	13.9 ± 0.2	-	53 ± 3	3.78 ± 0.24
LEW 85335.5	H6	Silicate	13.8 ± 0.1	12.4 ± 0.1	48 ± 2	42 ± 2	3.40 ± 0.17
LEW 86015.14	H6	Silicate	16.0 ± 0.5	13.5 ± 0.3	44 ± 2	33.7 ± 1.5	2.50 ± 0.13
LEW 86015.14	H6	Bulk	-	13.7 ± 0.2	-	34.3 ± 1.9	2.50 ± 0.14
LEW 86017.15	H6	Silicate	15.9 ± 0.1	13.8 ± 0.1	48 ± 2	40 ± 2	2.87 ± 0.15
LEW 85340.9	L5	Silicate	18.9 ± 0.1	17.3 ± 0.1	52 ± 2	46 ± 2	2.66 ± 0.14
LEW 85321.3	L6	Silicate	13.4 ± 0.2	12.8 ± 0.2	44 ± 3	40 ± 2	3.09 ± 0.17
LEW 85325.11	L6	Silicate	17.8 ± 0.3	16.9 ± 0.3	56 ± 3	52 ± 3	3.09 ± 0.16
LEW 85472.0	L6	Silicate	18.0 ± 0.2	17.1 ± 0.2	52 ± 3	49 ± 2	2.86 ± 0.14
LEW 86011.10	L6	Silicate	7.07 ± 0.11	6.36 ± 0.10	32.5 ± 1.5	28.3 ± 1.3	4.45 ± 0.22
LEW 86012.12	L6	Silicate	7.15 ± 0.16	6.72 ± 0.15	35.9 ± 1.7	33.0 ± 1.6	4.91 ± 0.25
LEW 86012.12	L6	Bulk	-	6.63 ± 0.14	-	30.0 ± 1.1	4.52 ± 0.18
LEW 86013.11	L6	Silicate	7.02 ± 0.12	6.74 ± 0.12	32.7 ± 1.7	31.1 ± 1.7	4.61 ± 0.26
LEW 86013.11	L6	Bulk	-	6.60 ± 0.11	-	30.7 ± 1.2	4.65 ± 0.20
LEW 86019.7	L6	Silicate	6.73 ± 0.17	6.36 ± 0.16	31.7 ± 1.7	29.5 ± 1.6	4.64 ± 0.28
LEW 86016.3	L6	Silicate	13.2 ± 0.2	12.6 ± 0.2	69 ± 3	64 ± 3	5.08 ± 0.25
LEW 86025.12	L6	Silicate	20.8 ± 0.1	20.2 ± 0.1	53 ± 3	51 ± 3	2.53 ± 0.13
LEW 86085.8	L6	Silicate	14.0 ± 0.2	12.6 ± 0.2	58 ± 3	50 ± 2	3.99 ± 0.20
LEW 87035.7	L6	Silicate	18.5 ± 0.2	17.7 ± 0.2	56 ± 3	53 ± 3	3.00 ± 0.15
LEW 87042.8	L6	Silicate	18.1 ± 0.2	17.5 ± 0.2	60 ± 3	57 ± 3	3.27 ± 0.16
LEW 87046.8	L6	Silicate	19.0 ± 0.2	18.2 ± 0.2	63 ± 3	59 ± 3	3.27 ± 0.17
LEW 87143.4	L6	Silicate	21.0 ± 0.3	20.2 ± 0.3	70 ± 3	67 ± 3	3.29 ± 0.16
LEW 87143.4	L6	Bulk	-	20.7 ± 0.3	-	-	-
LEW 87169.6	L6	Silicate	17.5 ± 0.3	16.4 ± 0.3	98 ± 4	92 ± 4	5.58 ± 0.29
LEW 87169.6	L6	Bulk	-	16.3 ± 0.3	-	96 ± 5	5.91 ± 0.35
LEW 88016.5	L6	Silicate	17.7 ± 0.1	16.1 ± 0.1	51 ± 2	45 ± 2	2.81 ± 0.14
LEW 88018.4	L6	Silicate	20.0 ± 0.1	19.2 ± 0.1	58 ± 3	55 ± 3	2.89 ± 0.14
UTRECHT-SP92	L6	Bulk	-	18.7 ± 0.3	-	55 ± 3	2.96 ± 0.16
UTRECHT-SP92	L6	Bulk	-	19.2 ± 0.3	-	58 ± 3	3.03 ± 0.14

^{a}) based on AMS results, assuming a ^{10}Be/^{9}Be ratio of 3.02 x 10^{-11} for SRM 4325 and a half-life of 1.51 Ma for ^{10}Be [7], ^{b}) based on AMS results assuming a half-life of 705 ka for ^{26}Al, ^{c}) for silicate samples, bulk values are deduced from measurements on the silicate fraction by taking the metal/silicate ratio and the ^{10}Be and ^{26}Al production rates in bulk OC's and metal phase into account.

more light on this problem. The low-NTL group of Fig. 2 contains three L6 chondrites (87143, 88190, and 87169) with "oversaturated" ^{26}Al activities, ranging from 69 to 96 dpm/kg. These high ^{26}Al values can be explained by the contribution of ^{26}Al produced by solar cosmic rays (SCR), indicating a low-perihelion (<0.85 AU) orbit. During low-perihelion passage meteorites are also exposed to solar heating, which explains the low NTL values. High SCR fluxes result in increased ^{26}Al contents in the outer few centimeters of a meteoroid and will therefore only be observed in those low-NTL meteorites, which also suffered low atmospheric ablation. The high ^{26}Al value of LEW 88013 does not coincide with a low NTL value and therefore cannot be unambiguously attributed to SCR-produced ^{26}Al. A large preatmospheric size (r = 40–50 cm) would also explain this high ^{26}Al value [13].

AMS results of ^{10}Be and ^{26}Al. The ^{10}Be and ^{26}Al results of 29 Lewis Cliff meteorites and the Utrecht L6 chondrite as a modern reference (fall, 1843) are listed in Table 2. For eight meteorites both a bulk sample and a silicate fraction were measured to check the consistency of our normalization procedure. This procedure converts values obtained on silicate samples into bulk values by taking into account the metal/silicate ratios and the ^{10}Be and ^{26}Al production rates for metal and silicate fractions. The comparison shows that the procedure is adequate within the error limits. Twenty-six of the meteorites listed in Table 2 were also measured in our γ-ray survey (Table 1). Except for LEW 86534, which shows a γ-ray ^{26}Al activity of 37 ± 4 dpm/kg vs. an average AMS value of 53 ± 2 dpm/kg, the results fall on a line with a slope of 1.03 ± 0.02. Terrestrial ages of Antarctic meteorites can be deduced from their ^{26}Al activity (A_{26}) by assuming an L-normalized saturation value of 60 dpm/kg and a half-life of 705 k.y. However, for a meteorite that never reached the saturation level, the resulting value is an "apparent" terrestrial age that must be corrected for its short exposure age. Due to the longer half-life of ^{10}Be (t 1/2 = 1.51 Ma) a correction can be made on the basis of the ^{10}Be activity. In Fig. 3 we plotted A_{26}/A_{10}, the measured ^{26}Al/^{10}Be activity ratio, vs. the "apparent" terrestrial age of each meteorite. Whereas the individual ^{10}Be and ^{26}Al production rates vary up to 30% due to shielding effects, their ratio appears to show variations of less than 10% for objects within a wide range of preatmospheric radii [13]. With an L-normalized saturation value of 20 dpm/kg for ^{10}Be, the A_{26}/A_{10} ratio at saturation is 3.0 ± 0.3, as is indeed found for the Utrecht chondrite (Table 2). Higher ratios are the result of short exposure ages (<5 Ma); lower ratios are due to radioactive decay of ^{26}Al and ^{10}Be during residence on Earth. This dependence of the A_{26}/A_{10} ratio on exposure age and terrestrial age is respresented in Fig. 3 by a two-dimensional grid. The terrestrial age coordinate of this grid represents the change in time of the A_{26}/A_{10} ratio, which decreases by a factor of 2 each 1.32 Ma. By following for each data point the directions of the grid lines one arrives at the corresponding values for the exposure age and the terrestrial age respectively.

The corrected terrestrial ages thus obtained for the 29 samples plotted in Fig. 3 range up to 500 k.y. The terrestrial age distribution (Fig. 4) corrected for two pairing groups (numbers 13 and 14) shows a peak at low values (<100 k.y.) as well as a small peak between 150 and 250 k.y. The general shape of this distribution is similar to that of Nishiizumi's distribution of terrestrial ages based on AMS ^{36}Cl measurements of 28 Lewis Cliff meteorites [14]. However, in the latter distribution the peak at low ages is more pronounced (64% of the cases vs. 29% in our data). We should point out that this

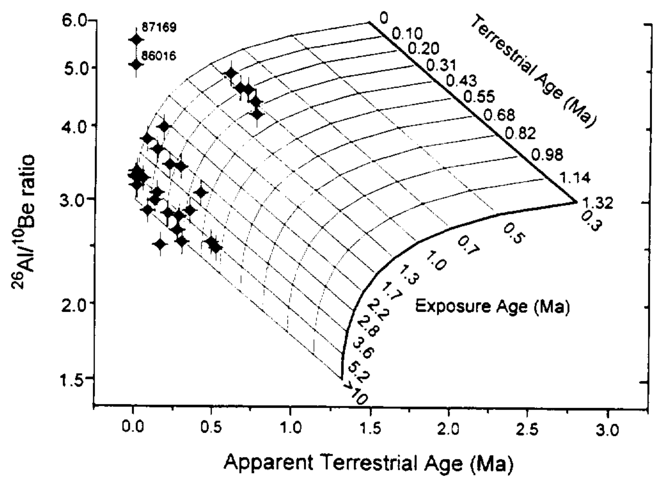

Fig. 3. Exposure and terrestrial ages of Lewis Cliff meteorites.

difference might be explained by shielding effects, because the terrestrial ages of meteorites with small preatmospheric sizes (r < 15 cm) are still overestimated in our approach. Additional ^{36}Cl measurements (in progress) will provide more definite answers.

Two meteorites plotted in Fig. 3 show A_{26}/A_{10} ratios well above the grid. Because one of these (LEW 87169) most likely contains SCR-produced ^{26}Al, this might also be the case for the other meteorite (LEW 86016), although its ^{26}Al activity of 64 dpm/kg does not significantly hint at "oversaturation." More cosmogenic nuclide data are required to shed light on its (unusual?) exposure history. Figure 3 reveals a cluster of five meteorites with short exposure ages of about 1 Ma. The upper four, L6 chondrites from Meteorite Moraine, are probably—in view of their similarly low ^{10}Be and ^{26}Al values (Table 2)—fragments of a single fall. The fifth meteorite, an H5 chondrite, reveals a terrestrial age of 330 ± 60 k.y., which is in agreement with the independently determined ^{36}Cl age of 300 ± 60 k.y. [15].

Pairing. Several potential pairings have been suggested by others on the basis of location, chemical-petrological classification, and NTL results [5,6]. Cosmogenic nuclide data provide additional and important clues in identifying or excluding pairings. Also, the

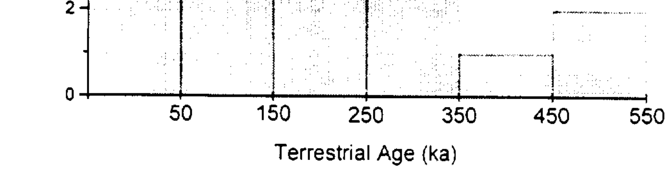

Fig. 4. Terrestrial ages of 24 Lewis Cliff OCs.

K contents obtained in our γ-ray survey serve as an additional pairing criterion. Of the 85 meteorites measured, 54 specimen could be assigned to 16 different pairing groups, each with 2–6 members, as indicated in Table 1. Of these 16 groups, only one pairing (88019 and 88020) was already suggested on the basis of their classification and proximity on the ice field [5]. Some of the pairings suggested on the basis of TL and other data [6] were confirmed, whereas others could be rejected. Due to analytical uncertainties and shielding effects it is usually difficult to identify pairs with absolute certainty. Therefore we used the confidence levels a (probably paired), b (tentatively paired), c (possibly paired), and x (unpaired) introduced by Scott [16].

We assigned two groups with confidence level a, five with level b, and nine with level c. Since for the remaining 31 meteorites pairing can be excluded, the 85 specimens represent at least 47 falls. The upper limit for individual falls amounts to 70 if only the a and b pairings are taken into account. Since some of the assigned c pairings may later, when more data become available, prove to represent individual falls, we estimate the total number of individual falls between 50 and 60. This brings the average number of fragments per fall for the Lewis Cliff area to 1.5. However, for two reasons this value must be considered as a lower limit: (1) our sample selection is biased to specimens larger than 50 g, whereas it is known that the number of fragments increases toward smaller sizes; and (2) we only considered pairings between meteorites found fairly close to each other, i.e., on the same field, either Lower Ice Tongue, Upper Ice Tongue, Meteorite Moraine, South Lewis Cliff, or Upper Walcott Névé. This implies that the average number of fragments per fall for the Lewis Cliff stranding area will be close to or within the range of 2–6 fragments per fall, as estimated by Scott on the basis of 300 Allan Hills meteorites [16,17].

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EXPOSURE AND TERRESTRIAL AGES OF H CHONDRITES FROM FRONTIER MOUNTAIN.

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Meteorite populations from geographically distinct locations in Antarctica have different terrestrial age distributions. For example, meteorites found in the Allan Hills Main Ice Field have ages of up to a million years, whereas Yamato specimens are rarely more than 200,000 yr old [1–3]. Prior to this work, only a few terrestrial age data have been reported for meteorites from the Frontier Mountain location (FRO) in North Victoria Land. Delisle et al. [4] give terrestrial ages for three FRO meteorites found during the 1984–1985 field season, based on ^{26}Al concentrations: FRO 8401, $(3.8 \pm 1.3) \times 10^5$ yr; FRO 8403, $(7.1 \pm 1.3) \times 10^5$ yr; FRO 8421, $(3.0 \pm 1.3) \times 10^5$ yr. These researchers observed from their limited dataset that Frontier Mountain meteorites displayed a similer range in residence times on Earth as other samples collected in Victoria Land. However, the one reported terrestrial age of a Frontier Mountain specimen based on ^{36}Cl disagrees with its ^{26}Al derived value: Nishiizumi et al. [1] state for FRO 8403 an age of $(1.2 \pm 1.0) \times 10^5$ yr, nearly 7× lower than the value given in [4].

Due to its half-life of 301,000 yr, ^{36}Cl is better suited than ^{26}Al to determine terrestrial ages in the 10^5-yr range. We therefore initiated a study of terrestrial ages of Frontier Mountain meteorites collected in the 1990–1991 season by analyzing ^{36}Cl in their metal fraction. We chose H chondrites of types 5 and 6 since this class yields the maximum amount of metal. The Frontier Mountain area and the find locations of the meteorites are described in [5]. Specimens labeled "Ice" in Table 1 were recovered on blue ice northeast of Frontier Mountain; specimens labeled "Mor." are from "Meteorite Moraine." Regional ice flow and the probable meteorite concentration mechanism are discussed in [4].

We present He, Ne, Ar, as well as ^{36}Cl data of 12 Frontier Mountain meteorites. Judged by these data, the 12 samples seem to represent at least 8 different falls. Pairing of the two solar-gas-rich samples FRO 90002 and FRO 90043 cannot be excluded and a common fall of FRO 90001, FRO 90050, FRO 90073, and FRO 90152 is suggested by their low ^{4}He concentrations and low $(^3He/^{21}Ne)_{cos}$ ratios, together with their similar $^{21}Ne_{cos}$ and $(^{22}Ne/^{21}Ne)_{cos}$ values. The parent meteorite of these four samples probably lost cosmogenic and radiogenic He. For each of the other specimens, find location, ^{36}Cl activity, and/or noble gas signature suggest an individual fall.

Neon-21 exposure ages are calculated according to Graf et al. [6] and Eugster [7], in both cases using the $(^{22}Ne/^{21}Ne)_{cos}$ ratio as shielding parameter. No shielding information is available for the two solar-gas-bearing samples, for which we therefore assumed "average" shielding, i.e., $(^{22}Ne/^{21}Ne)_{cos} = 1.11$, and report the exposure ages in parentheses. Ages derived by the two methods agree well for samples with $(^{22}Ne/^{21}Ne)_{cos} \geq 1.09$. This means that both methods assume a similar dependence between the ^{21}Ne production rate (P21) and $(^{22}Ne/^{21}Ne)_{cos}$ for relatively low shielding. To derive P21 with the Graf et al. method, we assumed an upper limit of 30 cm for the preatmospheric radius "R" of all meteorites with $(^{22}Ne/^{21}Ne)_{cos} \leq 1.09$. If we assumed larger preatmospheric radii, the upper bound of the exposure age interval derived for each sample would be correspondingly higher. The Eugster method does not explicitly make a similar assumption about R. However, since the variation of P21 with $(^{22}Ne/^{21}Ne)_{cos}$ used by Eugster [cf. 8] has been derived with data from more than 100 meteorites that for the most part can be assumed to have had a preatmospheric radius of less than 30 cm, the Eugster formula is valid also only for meteorites within this limited size range. Samples with $(^{22}Ne/^{21}Ne)_{cos} \leq 1.08$ had a preatmospheric radius exceeding 30 cm, according to the Graf et al. model. We present only minimum ages for these four samples, which may all belong to the same fall. These minimum ages are up to 2.2× higher than the respective values derived by the Eugster method. One reason for this discrepancy is that the P21 vs. $(^{22}Ne/$

TABLE 1. Noble gases and exposure ages in H chondrites from Frontier Mountain.

FRO..	Type/	Location	^{3}He	^{4}He	^{20}Ne	^{21}Ne	20/22	^{36}Ar	36/38	^{40}Ar	cosmogenic fraction ^{21}Ne	^{38}Ar	3/21	22/21	exposure age Graf	Eugster
90001	H6	Ice	3.26	386	1.632	1.745	0.885	0.516	2.065	3070	1.745	0.174	1.87	1.055	>8.7	4.3
90002	H5-6	Ice	8.78	10900	36.7	1.380	8.25	2.463	4.09	4650	1.29	0.165	(4.0)		(4.0)	(4.2)
90024	H5	Mor.	4.13	1930	2.168	1.922	1.014	0.556	1.504	51	1.921	0.301	2.15	1.09	5.5-5.8	5.7
90043[1]	H6	Ice	14.09	27800	125.6	1.849	10.64	7.27	4.78	4920	1.54	0.20			(4.8)	(5.0)
90048	H6	Ice	45.8	1780	6.37	6.08	0.836	0.981	0.966	5410	6.06	0.943	7.55	1.240	31.7-33.5	31.1
90050[2]	H5	Ice	3.96	458	1.523	1.520	0.926	0.914	3.72	3950	1.520	0.085	2.61	1.075	>4.5	4.1
90059	H5	Ice	5.72	1090	1.089	1.139	0.851	0.739	2.84	4620	1.139	0.138	5.03	1.120	3.6-3.8	3.9
90069	H6	Ice	9.70	1430	1.793	1.902	0.843	0.598	1.798	5310	1.902	0.250	5.10	1.115	6.1-6.3	6.3
90072	H5	Ice	12.61	1605	1.835	1.843	0.827	0.841	2.18	4970	1.843	0.259	6.84	1.195	8.7-9.0	8.2
90073[2]	H6	Ice	3.03	338	1.512	1.635	0.880	0.434	2.02	2790	1.635	0.151	1.85	1.050	>8.6	3.9
90082	H5	Mor.	13.66	1390	1.955	1.888	0.839	0.613	1.792	4820	1.885	0.258	7.24	1.220	9.8-10.1	9.1
90152[2]	H5	Ice	3.54	352	1.674	1.777	0.885	0.387	1.620	2240	1.777	0.189	1.99	1.060	>6.6	4.5

Gas concentrations in [10^{-8}cm^{3}STP/g]. Errors: 4% for gas concentrations, 0.5% for isotope ratios. Locations "Ice" and "Mor." explained in text. Cosmogenic ^{3}He, ^{21}Ne, ^{22}Ne/^{21}Ne, and ^{38}Ar calculated by assuming a solar composition for the trapped component in FRO90002 and FRO90043 and atmospheric trapped Ne and Ar otherwise. Shielding corrected ^{21}Ne exposure ages [Ma] calculated according to Graf et al. [6] and Eugster [7]. Ages in parentheses calculated with "average" shielding, i. e. $(^{22}Ne/^{21}Ne)_{cos}$ = 1.11.
1) Possibly paired with FRO90002. 2) Possibly paired with FRO90001.

$^{21}Ne)_{cos}$ correlation used by Eugster fails for $(^{22}Ne/^{21}Ne)_{cos} \leq 1.08$. Instead of becoming ever larger with increasing shielding, P21 will actually decrease in very big meteorites. However, it is not clear either how well the Graf et al. model extrapolates toward heavy shielding. It seems possible that the maximum ^{21}Ne production rates around $(^{22}Ne/^{21}Ne)_{cos}$ = 1.05–1.06 are underestimated by the model and that the minimum exposure ages thus become too high. In summary, ^{21}Ne exposure ages derived from heavily shielded samples are still quite uncertain. We therefore exclude the FRO 90001 clan from the following discussion.

Of the remaining eight samples in Table 1, only one has an exposure age clearly outside the 7-Ma peak so conspicuous for H chondrites [9,10], and the exception (FRO 90048) coincides with the other well-established H-chondrite peak at about 33 Ma [10]. It

TABLE 2. ^{36}Cl in metal and terrestrial ages.

FRO...	mass (mg)	^{36}Cl (dpm/kg)*	Terrestrial Age† (k.y.)
90001	85	21.42 ± 0.24	15 + 55/–15
90002	82	19.93 ± 0.23	45 + 55/–45
90024	83	14.15 ± 0.26	195 ± 65
90043	108	18.90 ± 0.21	70 ± 0
90048	109	20.76 ± 0.72	30 + 65/–30
90050	49	20.30 ± 0.22	35 + 55/–35
90059	100	19.59 ± 0.24	55 ± 55
90069	86	23.68 ± 0.34	<65
90072	113	22.89 ± 0.32	<40
90073	116	20.63 ± 0.29	30 + 55/–30
90082	52	17.33 ± 0.28	10 ± 60
90152	89	20.69 ± 0.37	30 + 60/–30
8403‡	97	17.19 ± 1.50	110 ± 90

* 1σ error.
† Terrestrial age calculated with saturation activity of ^{36}Cl (metal) = (22.1 ± 2.7) dpm/kg (2σ).
‡ Data from [1].

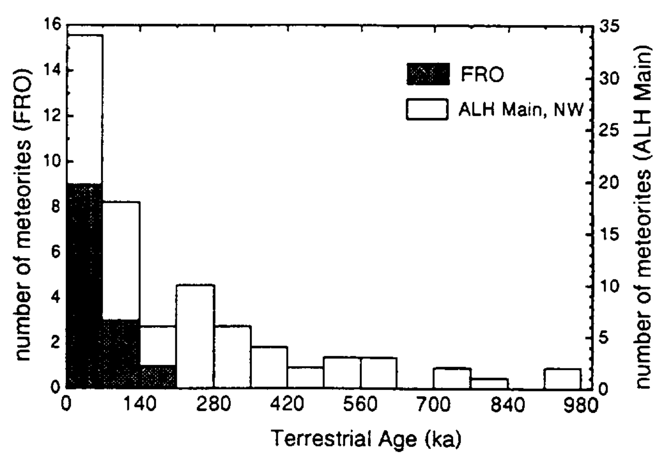

Fig. 1. Histogram of terrestrial ages of H chondrites from Frontier Mountain (this work, Table 2). The age distribution for meteorites from the Allan Hills Main and Near Western Ice Fields [3] is also shown for comparison.

is ambiguous how many of the remaining samples really belong to the 7-Ma peak. Marti and Graf [10] note another peak at ~4 Ma for H5 and H6 chondrites, and indeed, two or three of our samples may belong to this peak (90002/90043, 90024?, 90059). This would leave two to four samples in the 7-Ma peak (90024?, 90069, 90072, 90082?).

Chlorine-36 data and terrestrial ages derived from these values are presented in Table 2. The ages are calculated with a saturation activity of ^{36}Cl in the metal phase of chondrites of (22.1 ± 2.7) dpm/kg (2σ, unpublished). This current best estimate is based on depth profiles in Knyahinya and St. Severin [11] as well as 24 analyses of meteorites with known terrestrial age. The terrestrial age histogram of the Frontier Mountain samples is shown in Fig. 1. The two specimens recovered on Meteorite Moraine show the highest values of roughly 200,000 and 100,000 yr, respectively, whereas all other samples have been on Earth for probably less than 100,000 yr. It can reasonably be expected from the ice flow pattern near Frontier Mountain that meteorites in the moraine have larger terrestrial ages than those on the blue ice. Additional samples from the moraine will be analyzed to verify this difference.

All 13 Frontier Mountain meteorites analyzed so far for ^{36}Cl have terrestrial ages below 260,000 yr. The age distribution in Fig. 1 is thus similar to those usually found in Antarctica [1–3]. An exception is the Allan Hills Main Ice Field, for which the terrestrial ages are shown in Fig. 1 for comparison [3]. We conclude that Frontier Mountain meteorites on average have lower terrestrial ages than those from the Allan Hills Main Ice Field.

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CARBON-14 TERRESTRIAL AGES OF METEORITES FROM ACFER, ALGERIA.

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The Reg el Acfer in Algeria is a uniform stony desert area ~30 × 100 km. More than 300 meteorites have been collected here [1]. Because of the comparatively small collection area with uniform climatic and soil conditions, storage conditions for meteorites found here are very similar. The meteorite population thus offers a unique opportunity to study the relationship between terrestrial age and weathering, with the ultimate goal of estimating the total meteorite influx.

The terrestrial age was determined by the ^{14}C method. Small samples of 0.1–0.5 g can be ^{14}C dated using accelerator mass spectrometry [2–4]. Jull et al. [2] and Reedy et al. [5] used Knyahinya, Bruderheim, and some other chondrites to establish a saturated activity reference level. The production rate of ^{14}C varies with depth

TABLE 1. ^{14}C terrestrial ages of Algerian meteorites.

Sample	Type	WG*	^{14}C (dpm/kg)	Terrestrial age (k.y.) ± 1.3
El Djouf 003	L6	W4†	11.8 ± 0.15	12.1
Ilafegh 011	L5	W3†	6.3 ± 0.1	17.3
Acfer 019	L6	W3†	4.7 ± 0.1	19.8
Acfer 047	L4	W2	18.5 ± 0.2	8.4
Acfer 074	L6	W5	3.9 ± 0.1	21.2
Acfer 111	H3	W1	35.2 ± 0.3	2.3
Acfer 194	H5	W2	30.4 ± 0.2	3.5
Acfer 195	H6	W1	48.8 ± 0.8	recent fall
Acfer 197	L6	W2	17.3 ± 0.2	9.0
Acfer 198	H6	W1	37.5 ± 0.2	1.8
Acfer 199	L4	W3	24.6 ± 0.2	6.0
Acfer 200	H3–6	W1	27.5 ± 0.3	4.3
Acfer 201	L5	W2	10.4 ± 0.1	13.2
Acfer 203	H5	W3	32.8 ± 0.2	2.9
Acfer 204	H3	W2	12.3 ± 0.3	10.9
Acfer 205	H5	W2	11.2 ± 0.2	11.8
Acfer 206	H5	W1	46.1 ± 0.6	recent fall
Acfer 208	LL5/6	W3†	42.2 ± 0.2	2.2
	—	—	42.1 ± 0.3	2.2
Acfer 210	H3	W3†	2.67 ± 0.08	23.6
Acfer 212	H5	W5	8.6 ± 0.1	13.9
	—	—	9.7 ± 0.7	13.0
Acfer 215	L5	W1	4.8 ± 0.1	19.5
Acfer 216	L6	W2	18.2 ± 1.3	8.5 ‡
Acfer 218	L6	W5	5.45 ± 0.53	18.5
Acfer 219	H6	W1	13.3 ± 0.2	10.4
Acfer 221	H5–6	W2	17.2 ± 0.4	8.2
Acfer 223	LL6	W3	8.3 ± 0.1	15.6
Acfer 225	H3	W2	20.2 ± 0.5	6.9
Acfer 226	H5	W2	16.2 ± 0.1	8.7
Residue	—	—	20.0 ± 0.2	8.4
Acfer 227	H6	W1	26.0 ± 0.6	4.8
Residue	—	—	22.3 ± 0.3	6.0
Acfer 229	H5	W4	4.8 ± 0.4	18.8
Acfer 236	LL6	W2†	41.7 ± 0.2	2.3
Acfer 244	H5–6	W1	34.5 ± 0.2	2.5
	—	—	33.9 ± 0.3	2.6
Acfer 249	H5–6	W3	23.5 ± 0.5	5.6
Acfer 263	L6	W1	31.3 ± 0.4	4.0
	—	—	33.7 ± 0.3	3.4
Acfer 274	H6	W3	2.8 ± 0.1	23.2
Acfer 276	H5	W3	7.7 ± 0.1	14.8
Acfer 280	L6	W4	10.4 ± 0.1	13.1
Acfer 281	L5	W4	10.2 ± 0.1	13.3‡
Acfer 287	E4	W4†	29.0 ± 0.3	2.9
Acfer 288	L5	W3	7.1 ± 0.1	16.3
Acfer 290	L6	W3	1.5 ± 0.1	29.
Acfer 291	H6	W2	16.6 ± 0.1	8.5
Acfer 292	H5	W2	18.5 ± 1.3	7.6
Acfer 296	LL5–6	W2†	15.4 ± 0.1	10.6
Acfer 298	L6	W5	<0.30	>42.4
Acfer 302	H5	W3	16.1 ± 0.2	8.8
Acfer 303	H5–6	W3	13.3 ± 0.2	10.3
Acfer 305	L6	W5	7.6 ± 0.6	15.1 ± 1.5
Acfer 306	L6	W3	18.5 ± 10.4	8.4
Acfer 307	L5	W2–5	1.0 ± 0.3	31.5 ± 3
Acfer 309	L6	W3	3.6 ± 0.5	22.0 ± 1.8
Acfer 310	H6	W3	11.9 ± 0.4	11.3
Acfer 315	L/LL6	W4	0.7 ± 0.5	35.5 ± 5.5

* WG = weathering grades: W1 minor, W2 moderate, W3 heavy, W4 total oxidation of metal and troilite, W5 beginning, W6 massive alteration of silicates.

† Weathering grade from [1].

‡ Age may be too low due to ^{14}C contamination by weathering products.

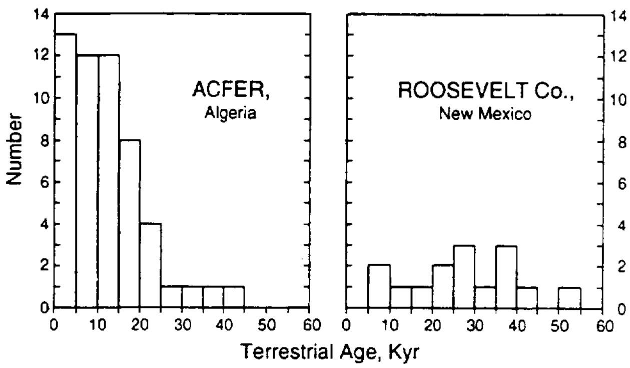

Fig. 1.

and the preatmospheric size of the meteoroid [5]. The precision of terrestrial age determinations is limited by these effects. Carbon-14 is of particular interest in warmer climatic regions, where the storage time before a meteorite weathers away is less than at many locations in Antarctica [3,6,7]. Carbon-14 ages have been obtained for meteorites from the semiarid high plains of the southwestern U.S. [3,8] and arid regions such as the western Libyan desert [6] and Western Australia [9]. The mean residence time of meteorites at such locations is well over 10,000 yr.

We have studied the ^{14}C age distribution of 53 meteorites from Algeria, 51 from the Acfer area (Table 1). Figure 1 presents the ^{14}C age distribution of these samples and shows a simple exponential dependence of terrestrial age vs. time. The oldest meteorites are at the limit of ^{14}C dating. A similar age relationship is observed for Western Australian meteorites ([9], see their Fig. 1 for a comparison with the Acfer data), but with fewer very old samples in the Australian case.

This is different from results seen for the southwestern U.S., especially Roosevelt County, New Mexico [3,8], where a higher proportion of old meteorites is found (Fig. 1). The less arid and colder high plains of Texas and New Mexico may be more conducive to storage of meteorites for longer periods of time than these areas (which is also shown by a comparison of terrestrial ages and weathering grades, as discussed below), but also we believe that older

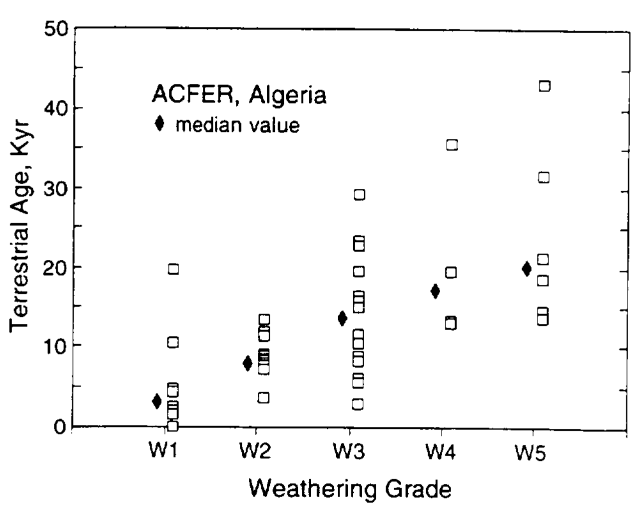

Fig. 2.

TABLE 2. Median terrestrial age (k.y.) for different WG of Acfer and Roosevelt County meteorites.

Weathering Grade	W1	W2	W3	W4	W5	W6
Acfer, Algeria	3	8	13	17	20	n.p.
Roosevelt Co., New Mexico	n.p.	8	22	27	35	40

n.p. = not present

meteorites may be stored in Pleistocene sediments at these sites, giving a deficit of "young" meteorites, as discussed by Jull et al. [9].

For the Acfer finds the weathering grade (WG) was determined in thin sections using the scheme of Wlotzka [10]. These grades register the degree of alteration of the meteorite minerals as a measure of the weathering intensity (see footnote to Table 1). For Acfer, we observe a dependence of WG on the ^{14}C age of the meteorite (Fig. 2), although the scatter of the data points is rather large. This shows that besides the residence time on the surface, individual properties of the meteorites, such as cracks and texture, must play a role. The highest ages in a given WG are found for meteorites of type L6 or L5, which suggests that a low metal content and recrystallized structure can delay the weathering effects. The opposite effect is seen in the E4 chondrite Acfer 287: It has already reached W4 in only 2.9 k.y. A better correlation is obtained for the median age vs. WG (Fig. 2). A similar correlation of WG with terrestrial age was first observed by us in Roosevelt County meteorites [8]. However, the median terrestrial age for a given WG is longer in Roosevelt County than in Acfer, at least for higher WGs (Table 2).

We have also studied the carbonates released by acid etching of the weathering products. We hope to relate trends in the amount of carbonate, $\delta^{13}C$, and ^{14}C age of the weathering products with the time of weathering and climatic effects.

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APPLYING THE BOOTSTRAP TO ANTARCTIC AND NON-ANTARCTIC H-CHONDRITE VOLATILE-TRACE-ELEMENT DATA.

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Recently developed bootstrap statistical methods are making a significant impact in the field of chemometrics. Bootstrap methods substitute iterative calculations for theoretical approximations used in many classical statistical techniques [1]. Randomization simulation [2] illustrates the application of the bootstrap method to the classical statistical techniques linear discriminant analysis and logistic regression as they are used to compare populations of Antarctic H and L chondrites to their non-Antarctic counterparts on the basis of volatile-trace-element composition. These techniques test the null hypothesis of no difference in volatile-trace-element composition between the two populations and calculate model-independent significance levels. Volatile-trace-element composition was selected for these tests because of its sensitivity to subtle thermal processes. By utilizing two different testing approaches, linear discriminant analysis and randomization simulation, we can assess the accuracy of model-dependent significance levels and determine whether discrimination is the result of invalid distributional assumptions, too many independent variables, or too few samples.

In this study we examine the suggestion that the flux of H-chondrite material has changed with respect to time [3]. A variety of differences have been observed between Antarctic and non-Antarctic meteorite populations ([4] and references therein). Comparisons of samples from Victoria Land and Queen Maud Land show differences in labile-trace-element contents [5] and induced thermoluminescence parameters [6]. H-chondrite meteorite populations from Victoria Land, Antarctica, Queen Maud Land, Antarctica, and modern falls have average terrestrial ages of 300 k.y., 100 k.y., and <200 yr respectively [7]. Here we compare each of these three populations to each other on the basis of the volatile-trace-elemental composition using multivariate linear discriminant analysis. Volatile-trace-element data exist for 117 H4–6 chondrites. The dataset includes Rb, Ag, Se, Cs, Te, Zn, Cd, Bi, Tl, and In (listed in order of increasing volatility). This dataset consists of 34 samples from Victoria Land, Antarctica, 25 samples from Queen Maud Land, Antarctica, and 58 modern falls. Multivariate linear discriminant analysis based on the concentrations of 10 volatile trace elements demonstrates that the terrestrial collection of H4–6 chondrites contains compositionally distinct subpopulations. Comparison between Antarctic and non-Antarctic, Victoria Land and non-Antarctic, Victoria Land and Queen Maud Land, Queen Maud Land and non-Antarctic H4–6 chondrites by linear discriminant analysis all reveal significant differences in volatile-trace-element composition (Table 1). Model-independent p values, calculated by linear-discriminant-analysis-based randomization simulation, differ to varying degrees with model-dependent p values. However, a significant difference in volatile trace element composition is indicated.

Both multivariate linear discriminant analysis and randomization simulation provide extremely strong evidence of a difference in volatile trace element composition between these three populations.

TABLE 1. Results of linear discriminant analysis and randomization simulation based on the concentrations of 10 volatile trace elements.

Population	# of Samples	Model-dependent p value	Model-independent p value
Antarctic	59	<0.0001	<0.001
non-Antarctic	58		
Victoria Land	34	0.0178	0.065
Queen Maud Land	25		
Victoria Land	34	<0.0001	<0.001
non-Antarctic	58		
Queen Maud Land	25	0.0002	0.002
non-Antarctic	58		

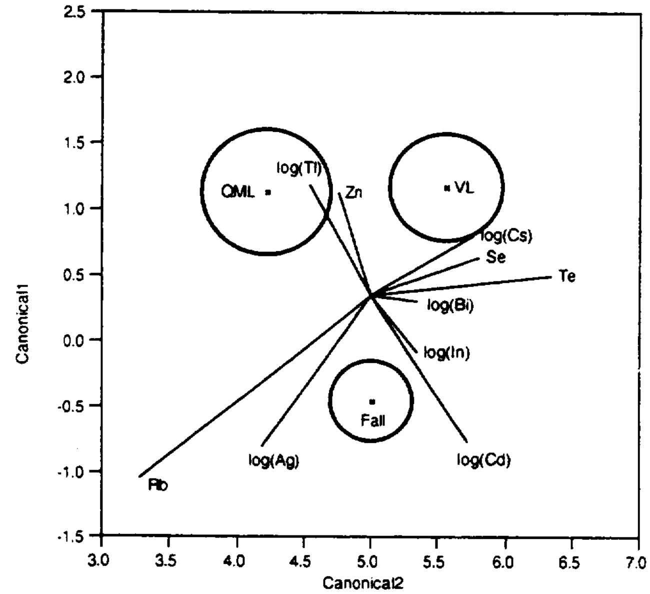

Fig. 1. Canonical details plot of volatile trace element composition of 34 Victoria Land, 25 Queen Maud Land, and 58 modern falls.

These techniques do not give the cause or causes of the observed differences. Insights into the causes of differences might be gained by determining the contribution that each element makes to discrimination. A method that allows the visualization of each element's contribution to discrimination is a canonical details plot (Fig. 1). This figure graphically illustrates the centroid of each population in two-dimensional canonical space. The centroids of each population appear with a circle corresponding to the 95% confidence region [8]. The elemental rays indicate the loading that these variables have on each dimension in this test space. Figure 1 suggests that all 10 volatile trace elements affect discrimination between these populations to varying degrees. However, the loading that each element has depends on which populations are being compared. Elements that load the highest when Antarctic (Victoria Land and Queen Maud Land) and non-Antarctic H4–6 chondrites are compared are Ag, Cd, and Tl. Rubidium, Cs, and Zn also load to a lesser degree. Discrimination between Victoria Land and Queen Maud Land H4–6 chon-

TABLE 2. Results of linear discriminant analysis and randomization simulation based on induced thermoluminescence properties peak temperature and peak width.

Population	# of Samples	Model-dependent p value	Model-independent p value
Antarctic	63	<0.0001	<0.006
non-Antarctic	48		
Victoria Land	43	0.0001	0.006
Queen Maud Land	20		
Victoria Land	43	<0.0001	<0.001
non-Antarctic	58		
Queen Maud Land	20	0.1812	0.538
non-Antarctic	48		

drite populations is dominated by Se, Cs, Te, and Bi. Discrimination between Queen Maud Land and non-Antarctic H4–6 chondrite populations is dominated by Ag, Cd, Tl, and In.

Possible causes of differences in volatile-trace-element composition include trivial causes such as sampling bias, analytical bias, pairing, and weathering. Similar differences in volatile-trace-element composition are revealed when canonical details of samples from a single analysis are plotted. Differences in volatile-trace-element composition are therefore inconsistent with sampling or analytical bias. Noble-gas and cosmogenic-nuclide data indicate that pairing of Antarctic samples is essentially nonexistent in our database [9,10]. All Victoria Land samples are of weathering type A, A/B, or B. Samples from Queen Maud Land were selected on the basis of minimal visible oxidation in the hand specimens. Differences in volatile-trace-element composition shown in Fig. 1 are inconsistent with leaching resulting from weathering. Differences observed between Victoria Land, Queen Maud Land, and modern falls are consistent with a temporally varying sampling of H4–6 chondrite material that is heterogeneous with respect to volatile trace elements. Different thermal histories for these three populations are indicated.

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YES, METEORITE POPULATIONS REACHING THE EARTH CHANGE WITH TIME!

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The answer provided by the title of this workshop contribution is based upon data obtained by radiochemical neutron activation analysis (RNAA) and accelerator mass spectrometry (AMS). We have chosen H4–6 chondrites as a paradigm. The RNAA measurements involve volatile trace and ultratrace elements (whose concentrations reflect the meteorites' preterrestrial thermal histories): The AMS results for cosmogenic 300-k.y. ^{36}Cl (and other longer-lived cosmogenic radionuclides) provide nominal terrestrial ages for Antarctic meteorites.

Time-dependent source changes of the meteorite flux in Earth—which are not predicted by existing statistical, Monte Carlo models for meteoroid dynamics—can be short-term and/or long-term. To assess these, we compare compositions of H-chondrite sample suites chosen by physical criteria that are independent of the meteorites' compositions. In each H chondrite, we measure 10 volatile (Rb, Ag, Se, Cs, Te, Zn, Cd, Bi, Tl, In) and a few other trace elements by RNAA. Since suite differences are subtle, we use well-established multivariate statistical techniques of linear discriminant analysis and logistic regression to classify the two sample suites compositionally and test the model-dependent level at which we can disprove the null hypothesis that the two sample suites derive from the same parent population. We also test this null hypothesis using a novel, model-independent approach—randomization simulation [1, 2]—that provides confidence levels at which we can assert that the suites being compared are compositionally distinguishable.

Short-Term Variations: Dodd et al. [3] determined from their circumstances of fall that a significant elongate cluster of 17 co-orbital H-chondrite falls (H Cluster 1) in May 1855–1895 records encounters with two or three closely spaced and probably related meteoroid stream components, each of which was met near perihelion. Meteorites of H Cluster 1 vary widely in petrographic type (3–6), shock facies (a–d), and ^{21}Ne exposure age (<5–50 m.y.). However, RNAA studies reveal that the volatile-trace-element signature of 13 of them is distinct from that of 45 other H4–6 chondrite falls not of H Cluster 1 (cf. Fig. 1). Hence, members of H Cluster 1 have a common thermal history, and thus derive from a common source region in an H-chondrite parent body. Similar studies are about to commence of additional H4–6 chondrite falls suspected to be members of other co-orbital streams, to test how general it is that H chondrites—like H Cluster 1—selected by one criterion (fall

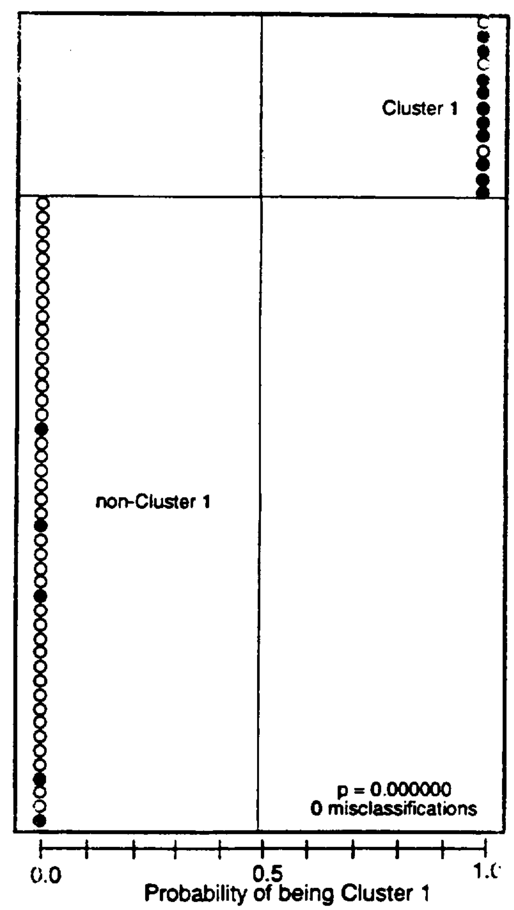

Fig. 1. Logistic regression based on data for 10 volatile trace elements reveals perfect separation of 13 H Cluster 1 falls from 45 other H4–6 chondrite falls, hence compelling evidence of a compositional difference. Sources of data: filled symbols [3], open symbols [14]. The compositional uniqueness of H Cluster 1 chondrites from all other falls signals that the cluster derives from a unique parent region.

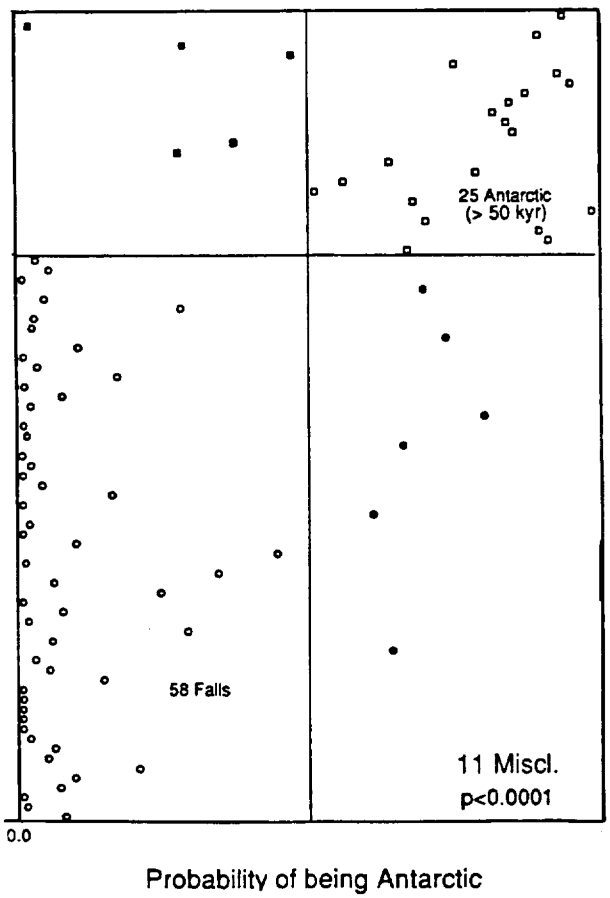

Fig. 2. Logistic regression based on data for 10 volatile trace elements reveals very good separation of 25 Antarctic H4–6 chondrites (nominal ter-restrial ages >50 k.y.) from 58 falls [11]. By model-dependent or model-independent methods, p values < 0.001 signal very strong evidence that these Antarctic H4–6 chondrites derive from source regions different than the one(s) that yielded contemporary H4–6 chondrite falls.

parameters) prove by another criterion (contents of volatile trace elements) to be significantly distinguishable from other H-chondrite falls.

In this connection, it is important to note that the fall period for H Cluster 1 chondrites (days 133–147) coincides with days on which the two known asteroids that approach the Earth most closely do so: 1993 KA_2, 0.0010 AU on day 140 (May 20); and 1993 KA, 0.0071 AU on day 137 (May 17) [3]. The latter is of particular interest since it is one of the surprisingly numerous asteroids that are co-orbital in an Earth-like orbit [4].

Long-Term Variations: To examine whether variations in the meteoroid flux to Earth occur on the 1000-yr timescale it is necessary to make measurements on meteorites found in Antarctica that have terrestrial ages ranging up to 1 m.y. Meteorites recovered from Victoria Land and from Queen Maud Land, Antarctica, have different terrestrial age distributions and mean terrestrial ages, 300 and 100 k.y. respectively [5].

There is no doubt that meteorites of rare types discovered in Antarctica differ markedly from those falling more recently elsewhere on Earth. Whether such Antarctic/non-Antarctic differences of a preterrestrial origin exist is more controversial.

It has been demonstrated that Antarctic H4–6 (and L4–6) chondrites mainly from Victoria Land are, on average, compositionally distinguishable from falls [1,6,7]. A significant difference between these suites is also detected by thermoluminescence [8] but not by noble gas measurements [9]. Some have argued that differences in contents of volatile trace elements in Antarctic and non-Antarctic H4–6 chondrites, for example, reflect weathering in Antarctica and/or are artifacts of the data treatment. These possibilities are discussed in detail elsewhere [10] and found not to be viable.

Significant compositional differences exist between H4–6 chondrite suites from Victoria Land (34 samples) and Queen Maud Land (25 samples), Antarctica, presumably reflecting mean terrestrial age differences [10]. This time-dependent compositional difference has been established directly by comparing the sample suite of 58 H4–6 chondrite falls with Antarctic suites having specific nominal terrestrial age ranges [11]. Compositionally, 13 Antarctic H4–6 chondrites with nominal terrestrial ages ≤50 k.y. are not significantly distinguishable from 58 falls, i.e., are consistent with the null hypothesis that these sample suites are drawn from the same parent population.

However, very different results are obtained when 12 Antarctic chondrites with nominal terrestrial ages of 50–70 k.y. or 13 Antarctic chondrites with nominal terrestrial ages ≥70 k.y. are studied: Each differs compositionally from 58 falls. When these two Antarctic suites are combined, the compositional distinction between 58 falls and the 25 samples with nominal terrestrial ages >50 k.y. is—like H Cluster 1—significant [11] beyond any reasonable doubt (Fig. 2). As a consequence of this time-dependent change, 34 Victoria Land H4–6 chondrites differ compositionally, on average, from 58 falls, while 25 from Queen Maud Land do not, i.e., are consistent with the null hypothesis that the Queen Maud Land suite and the suite of falls are drawn from the same parent population [12].

Hence, both on the short term and the long term, there is ample evidence that the Earth's sampling of meteoritic matter has varied with time. How this occurred dynamically is now being considered [4,13].

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THE ACQUISITION OF MARTIAN SEDIMENTARY ROCKS: FOR THE TIME BEING, COLLECTION OF METEORITES FROM TERRESTRIAL DESERT AREAS REPRESENTS THE BEST HOPE. I. P. Wright[1], M. M. Grady[2], and C. T. Pillinger[1], [1]Department of Earth Sciences, Open University, Walton Hall, Milton Keynes MK7 6AA, UK, [2]Natural History Museum, Cromwell Road, London SW7 5BD, UK.

In a recent paper, Wright and Pillinger [1] have discussed some of the problems of identification that would arise if a sedimentary rock of martian origin were to land on Earth as a meteorite (i.e., a sample that had been ejected from Mars and transported to Earth in the same way as its basaltic counterparts, the SNC meteorites). In a sense, this is not a newly recognized problem; the notional difficulties of recognizing the origins of meteorites, especially those with planetary affinities, have been outlined by, among others, Cross [2] and Nininger [3]. The confusion over assigning origins is further highlighted by the fact that, at one time, some rather illustrious scientists had postulated that meteorites in general may have had a lunar origin [e.g., 4]. Presumably the Moon was imagined to be a more complex place than it turned out to be. But these are thoughts from a previous era, being documented prior to the return of lunar samples by the Apollo and Luna missions of the late 1960s and early 1970s, and before the recent golden age of meteoritics when so many important advances have been made. There is now general agreement that most meteorites have origins from within the asteroid belt; indeed, certain asteroids have been proposed as the parent bodies of particular meteorite groups [e.g., 5,6]. It is thus ironic that meteorites of lunar origin, although comparatively rare, *have* now been identified [e.g., 7]. In this context the parent body can be considered to be more of a planetary nature rather than an asteroid. But, as planetary bodies go, the Moon is relatively uncomplicated, so any fragments that arrive on Earth will be relatively easy to identify. In consequence, recognition of lunar meteorites should in the future be fairly straightforward. Indeed, one has been collected from Australia. Note, however, that it is still possible to misidentify a lunar specimen [e.g., 8], especially when there is pressure to force meteorites into an established classification scheme [e.g., 9].

A far more challenging prospect for those interested in studying planetary meteorites is the quest for samples of sedimentary origin. Throughout the history of meteoritics, materials of this nature have been documented many times; in fact, they are so well established that the different categories have names [2,10], e.g., "amathosites" and "calcarites" are sandstone and limestone meteorites respectively. However, it has to be concluded that whatever samples are currently represented in the world's collections, they are most probably pseudometeorites (i.e., samples of terrestrial origin that, to some people at least, look like meteorites on account of their water-rounded surfaces, or coatings of desert varnish, etc.). The celebrated calcarite, Bleckenstad [11], is purported to contain fossils. But, a terrestrial rock could still be a meteorite. Indeed, Melosh and Tonks [12] have shown that some impact-ejected terrestrial materials could reside in space for 5 m.y. or so, before returning to the surface—these samples might be observed to fall, have a fusion crust, contain cosmogenically produced nuclides, etc. It seems likely, though, that meteorite curators through the ages, having been presented with a fossiliferous sedimentary rock, would probably not have been able to assess the true nature of such a terrestrial meteorite (notwithstanding the protestations of the owner). How many of these types of sample have been returned to sender? More pertinently perhaps, how many such samples are still preserved in traditional collections?

In some ways, recognition of terrestrial meteorites is only of academic interest; their main importance would be to document a past impact event. In contrast, meteorites from Mars are extremely valuable. Until appropriate samples can be returned to Earth by space missions, meteorites of martian origin represent the only way of conducting laboratory-based analyses of the planet. Ten samples of the martian crust have been recognized on Earth in the form of SNC meteorites (the evidence for a martian origin can be found in Wood and Ashwal [13] and McSween [14]). But as yet we have no samples of martian sedimentary material. This is certainly not because they do not exist, but is more likely because we have not yet learned to recognize them on Earth. What are currently represented on Earth in the form of SNC meteorites are samples of volcanic origin. Most of these materials are relatively fresh examples of shallow intrusive or extrusive basaltic rocks. Indeed, this has been, perhaps subliminally, one of the criteria used for their identification. That the samples are not completely unaltered was first documented by Ashworth and Hutchison [15] and Bunch and Reid [16]. However, the true relevance of the alteration products was not appreciated until the work of Carr et al. [17], who proposed that minerals such as carbonates were martian weathering products produced during their near-surface sojourn. Having established this fact, it became clear that the operation of martian surface processes could be investigated through detailed analysis of these trace weathering products [e.g., 18,19]. However, the overall picture is far from clear; for instance, it has subsequently been discovered that the sample with one of the highest contents of weathering products (Elephant Moraine A79001) also apparently contains high levels of ^{14}C, which seems to suggest a terrestrial origin for some of the carbonates in the sample [20]. Thus far this issue has not been resolved. On the other hand, the most recently identified SNC meteorite (ALH 84001) contains widely distributed, submillimeter concentrations of carbonates that are compositionally zoned and "clearly formed prior to arrival on Earth" [21]. Allan Hills 84001 was originally classified as a diogenite, a basaltic achondrite of asteroidal origin [21]; in fact, this "new" SNC meteorite is likely to prove pivotal in our understanding of martian surface processes. The carbonates appear to have been formed by hydrothermal alteration at temperatures of about 700°C. This poses the question: If the rock had been more extensively altered, would it have ever been identified as a martian meteorite?

On the basis of the surface features on Mars, which can be observed in the photographic records of Mariner 9 and the Viking orbiters, it is apparent that the geomorphology of Mars has been shaped by fluvial activity, winds, ancient oceans, etc. Models of surface evolution contend that there should be extensive carbonate deposits on Mars, perhaps buried within the regolith. Any impact event that has the power to eject samples of relatively fresh basaltic materials (i.e., from some depth within the crust) must also liberate representatives of the surface rocks. Let us consider the example of a carbonate deposit. If this is successfully transported to the surface of the Earth to arrive as a meteorite, it is interesting to speculate on the appearance of the sample. For instance, it will not have a traditional fusion crust (one of the classical pieces of evidence used to assess the validity of a meteorite). This is because as the sample falls through the Earth's atmosphere, heating at the surface of the sample causes decrepitation of carbonate minerals to a mineral oxide and gaseous CO_2 (the gas being lost instantly). In other words, in the case of calcite, $CaCO_3$ would be converted to CaO and CO_2. Since CaO has a melting point of 2850°C, the temperatures experienced during infall would never be sufficiently high to enable the production of a glassy fusion crust. Furthermore, upon arrival at the Earth's surface, the CaO would react with atmospheric or meteoric water to produce $Ca(OH)_2$, which in turn would absorb CO_2 from the air to form $CaCO_3$. Thus, at no time would the sample look like a classic meteorite. In conclusion, it is probable that recognition of this hypothetical meteorite could only be established by an observation of the fall, and this would have to be by a credible witness (would a member of the public be taken seriously?).

If sedimentary martian meteorites do exist, they will be present on the Antarctic ice fields. Since it will not be possible to recognize them for what they are in the field, the only way to ensure their collection is to return all samples from within a particular area (as advocated by Huss [22]). The daunting task of positive identification must utilize a rapid screening technique, preferably geochemical analysis of some sort. The most obvious and desirable approach would be to use O isotope determination, since this can be used to identify unambiguously most materials that are not terrestrial in origin (the exceptions being lunar samples, enstatite chondrites, and aubrites). On the other hand, a method specific to limestones, might simply involve C isotope analysis. Note that sedimentary meteorites will also be present in the hot deserts, but their retrieval is more problematic—it is not possible to conceive of collecting all rock samples from a particular area. However, members of collection parties can assist in the effort by being aware of materials that seem out of place (sandstones on a limestone platform, for instance). Thinking to the future, it is currently proposed to send mass spectrometers and extraction systems to Mars [23] and a comet [24] for the purpose of making remote stable isotopic measurements. If such instrumentation is developed, its low mass (2–5 kg) may enable the apparatus to be deployed in the field, so that potentially interesting materials could be identified *in situ*. In this way collection parties would not need to use industrial-scale Earth-moving equipment to transport a field season's samples back to curatorial facilities. In either case, the desired samples of the martian surface would be uncovered several decades before they can be returned to Earth by spacecraft.

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LOCATING NEW METEORITE RECOVERY AREAS.

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Introduction: Several years ago two of us (J.W.S. and M.E.Z.) resolved to visit Roosevelt County, New Mexico, to look for meteorites. We then decided that rather than search where others had before us, we would attempt to find a new meteorite concentration surface. Accordingly, we chose the general area south of Roosevelt County as the exploration target, and thought through the exercise of "how to predict where meteorites can be found." J.W.S. had considerable experience in the Antarctic Search for Meteorites, having served as ice guide and all-around expedition expert for many field seasons with Bill Cassidy. From the Antarctic experience and by extension from the Roosevelt County finds, we knew that target areas should exhibit the following characteristics.

Low Humidity: Aside from the polar deserts, most deserts straddle either the Tropic of Cancer or Capricorn (23.5° N and S latitude, respectively). These deserts include the Sahara, Arabian, Victoria (Australia), Kalahari and Namib (S. Africa), Sonoran (N. America), Atacama (S. America), Registan (Afghanistan), Baluchistan (Pakistan), and Great Indian Desert. The Takla Makan (north of Tibet) and Gobi and Kashmir (W. China) Deserts and those in the western U.S. are examples of topographic deserts, located deep inside continental masses, cut off from oceanic bodies and humid winds by mountains. Any of these deserts are potential target areas; few have been the subject of systematic searches. The locations of these deserts are all shown in Fig. 1.

Minimal Fluvial Activity: Stream activity should be minimal, so that little terrigenous material has been deposited or removed during the lifetime of meteorite accumulation and excavation.

Minimal Input of Terrestrial Rocks: Anyone who has spent time in Antarctica searching for meteorites in a glacial moraine crowded with black rocks will recognize the desirability of this characteristic. Surfaces are far more easily searched if there is little terrestrial material to obscure the meteorites. This requirement can be satisfied by geologically quiet, nonfluviatile areas with subdued topography.

Rapid Burial of Meteorites: For Antarctic meteorite concentrations, it is generally thought that most meteorites fall onto the ice cap far from the eventual stranding areas. They are subsequently buried by snow, which gradually compacts through firn to ice. In other places on Earth the most efficient burial may be performed by

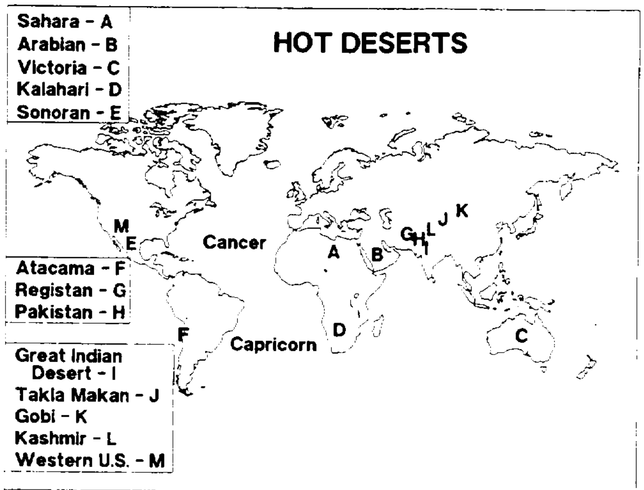

Fig. 1. Location map of hot deserts.

blowing sand. In any case, meteorite preservation is facilitated by rapid burial, and removal from the atmosphere.

Recent Deflation: In Antarctica the meteorites are concentrated by a combination of glacial movement and ablation of the ice carrying the meteorites. Elsewhere, the corollary to criterion 4 is relatively rapid meteorite excavation, by wind (deflation) or burrowing mammals. In the southwestern U.S. deflation is a cyclical phenomenon, where wet periods alternate with dry periods. During the wet periods, calcite, the principle cementing agent for local cover sands, can be leached away, promoting the removal of loosened sand grains during dry periods. Mammals can contribute to this process; in the 1950s large mammals working for the U.S. Department of Agriculture recommended to farmers living in Roosevelt County (New Mexico) that they plow up large tracts of grassland. Unfortunately, this conservation effort immediately preceded a period of drought and substantial winds, during which the previously fertile soils of the grasslands were stripped away, leaving large deflation basins in their place. The local economy was damaged, but hundreds of meteorites were exposed and subsequently recovered. A corollary of this criterion is that there must be minimal ground cover by plants.

Degree of Induration of the Stranding Surface: The final stranding surface must be sufficiently indurated to support meteorites so that they may be recovered. Even a thin layer of loose dust or sand blanketing the ground can effectively disguise meteorites in the same way that a recent snowfall can in the Antarctic. In the southwestern U.S., Pleistocene lacustrine beds make good stranding surfaces, as they are rich in Ca carbonates and consequently are well cemented.

Using these criteria, we should be able to select specific regions of Earth's surface for future meteorite recovery expeditions. How well will this scheme work? Let's examine three subsequent expeditions that were undertaken with these criteria as a guide.

Lea County, New Mexico: The high numbers of meteorites recovered in Roosevelt County indicated that additional finds might be made in similar landscapes to the south, in neighboring Lea County. In 1988, J.W.S. and M.E.Z. made foot searches of recent deflation basins exposing Late Pleistocene eolian sediments and topsoil in the region immediately south of Jal, New Mexico [1]. These deflation basins appeared to satisfy all criteria except number 4. The deflation basins in the Jal vicinity do not generally exceed 300×50 m in size, and the floors are a well-indurated, red- to gray-colored calcareous sandstone of possible lacustrine origin. These floor sediments appear to be 50–100 k.y. in age, in analogy to the deflation basins in Roosevelt County [2]. We found two chondrites in our foot searches (one H and one ungrouped), hardly a high concentration, but suggestive of further discoveries in the future. We are now performing a survey of additional similar sites immediately to the east in Texas. The widespread nature of Pleistocene lacustrine deposits in the Desert High Plains of the U.S. suggests that additional meteorite concentration surfaces will be found. It is probable that the rate-controlling step for these discoveries will be sudden intense deflation episodes.

Atacama Desert, Chile: The Atacama Desert is one of the driest regions on Earth. In 1991, E.M.R. and M.E.Z. made jeep and foot searches of large deflation surfaces situated between the Chilean city of Antofagasta and the seaside fishing village of Mejillones (an area called "Pampa"). The deflation surfaces are immediately inland of a broad coastal mountain (Cerro Moreno) that insulates the region from oceanic moisture. Pampa is an elevated beach deposit, and the surface is poorly indurated (so meteorite fragments are easily disguised by dust). Considering the remaining uncertainties concerning the local geological history, only criteria 1 and 2 are clearly satisfied by the Pampa area. Nevertheless, between those samples found previously by Edmundo Martinez and those found on the 1991 expedition, we (in concert with Rene Martinez) have described five (different) new L chondrites [3]. There appears to be significant future potential at this and adjacent sites. It is interesting that only L chondrites have been found at Pampa. One might think that the lower amount of metal in L chondrites, relative to H chondrites, might stabilize them with respect to terrestrial weathering. However, there is apparently no real indication of an enhancement like this for, say, the Antarctic finds relative to worldwide falls [4].

Namib Desert, Namibia: The Namib is one of the wettest deserts that have been searched for meteorites. It is located along the southwestern coast of Africa, with little in the way of barrier topography to shield it from oceanic moisture, which appears here in the form of frequent morning fog. The age of the Namib surfaces is subject to controversy, but is generally believed to be at least 5 Ma in places (see [5]). In 1991, A.M.R., P.J., and M.E.Z. performed reconnaissance foot searches of four different areas in and adjacent to the Namib, selected in advance with the assistance of Justin Wilkinson. These target areas were (1) along the fan delta of the Omaruru River, north and east of Henties Bay; (2) along river terraces south of the Swakop River, east of Swakopmund; (3) on deflation surfaces and interdune corridors within the Namib Sand Sea, west of Tsondabvlei and south of Gobabeb; and (4) on deflation surfaces east of Walvis Bay. Meteorites were only found in the last-mentioned locale, three ordinary chondrites (two unpaired Ls and one H) [5]. "Recent" fluvial activity may account for the lack of significant meteorite concentrations in locales 1 and 2. It is more difficult to account for the failure to locate meteorites in locale 3, where deflation surfaces of tremendous size were present (each measuring up to several kilometers across). We noticed that the surface at locale 3 was not well indurated, being covered with fine sand and lag deposit to a depth of several centimeters, and this may account for the apparent lack of meteorites, i.e., they were shielded from view by a thin layer of sand. The meteorite-producing locale, number 4, satisfied criteria 2, 3, and 5. It was also sufficiently inland to be fairly dry (criteria 1). The surface at this site was not particularly well indurated; however, the sand blanket was no more than 1 cm thick, in contrast to the other sites we searched in Namibia.

We conclude that, in addition to the six criteria proposed above, two other criteria should be considered when evaluating potential new areas for meteorite exploration:

Sand Cover Thickness: If the surface is not well indurated, then the depth of any loose sand cover is a critical factor; this should be very thin (≤1 cm).

Age: The age of the meteorite accumulation surface should be at least 100 k.y., to permit accumulation of a reasonable number of meteorites. This rather arbitrary age is proposed by analogy to the Roosevelt County meteorite accumulation surfaces.

We emphasize that luck plays a definite role in meteorite exploration, as does the very important ability to differentiate very weathered meteorites from the local rock population.

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